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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 1, PP. 3–15, FIGS. 1–11,
APRIL, 1936

HEAVY MINERAL ZONES IN THE MODELO FORMATION OF THE SANTA MONICA MOUNTAINS, CALIFORNIA

WILLIAM M. COGEN

Balch Graduate School of the Geological Sciences, California Institute of Technology
Pasadena, California.

ABSTRACT

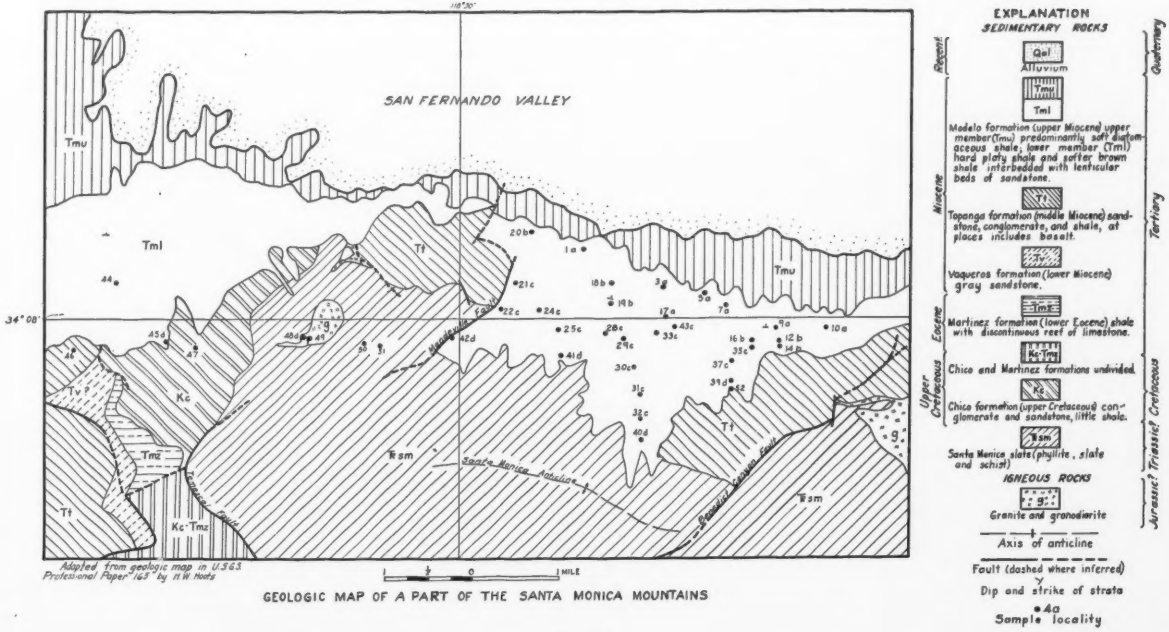
A detailed heavy mineral study was made of a portion of the Modelo formation in the Santa Monica Mountains, near Los Angeles. It was found that the heavy minerals varied both vertically in the formation and laterally within single lithologic units. Four distinct mineral zones were recognized. These zones transect the lithologic boundaries and the structure of the formation. The cause of the peculiar boundary relations between the mineral zones and the rock units is not clear. Whether or not the mineral zone boundaries are surfaces of contemporaneous deposition remains a moot question.

The purpose of this investigation was to ascertain the degree of lateral and vertical mineral variation that occurs in some Tertiary formations of California. Such information is fundamentally important for determining the usefulness of minerals as criteria for correlation. Reed had carried out an analogous examination in the Tertiary formations of the Coalinga district. He sampled a stratum two feet thick for a distance of two miles and showed that there was in general "a gratifying degree of similarity in the heavy mineral assemblages of the various samples" (13).

A section of the Modelo formation, on the north flank of the Santa Monica Mountains, was selected for this inquiry. This district lies about 18 miles northwest of Los Angeles, is readily accessible, and a good geologic map of the area is available (8).

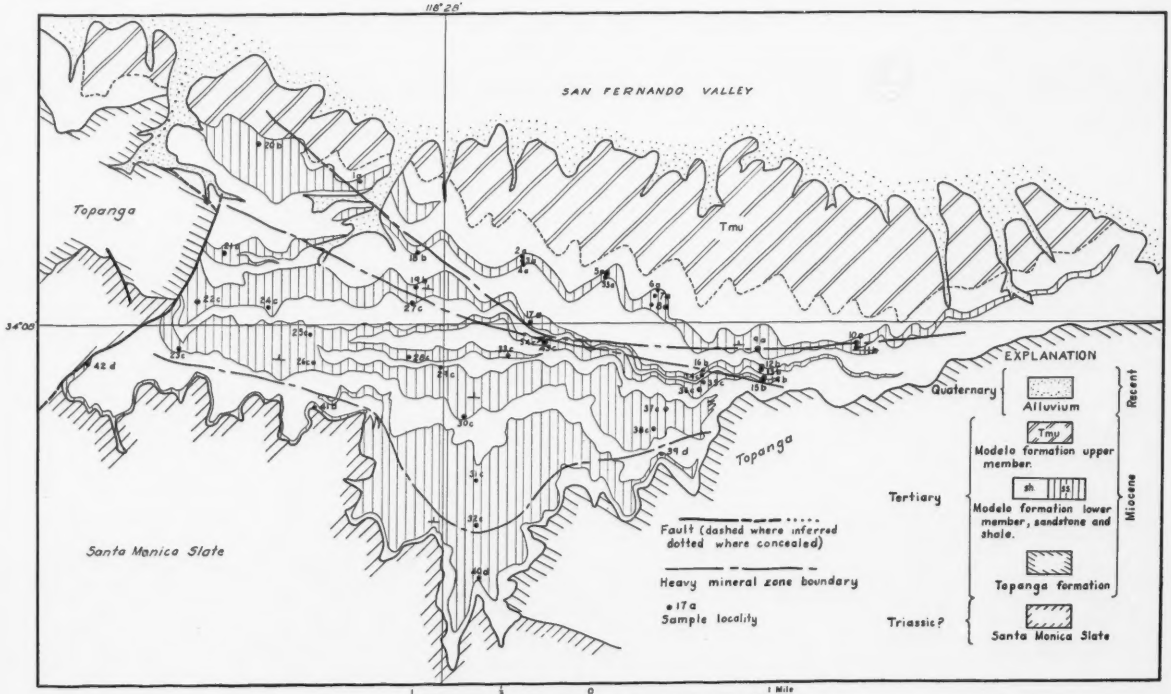
At this locality, the lower member of the Modelo formation, to which this investigation was confined, consists, with the exception of the basal greywacke, of several thick alternating units of fine-grained sandstone and shale. A dark greywacke, composed of angular slate fragments, generally occurs at the base of the Modelo where it directly overlies the Santa Monica slate. The sandstone units are dun colored and moderately indurated. The shale is grey and commonly sandy, becoming more siliceous toward the top of the formation. These lithologic units may be traced on the surface for several miles.

Except for the basal greywacke, the texture of the sandstone units in the Modelo of this locality is remarkably uniform, ranging from medium- to fine-grained. Screen analyses failed to show any definite textural trend laterally or vertically in the formation. The transition from sandstone to shale units is marked by a series



GEOLOGIC MAP OF A PART OF THE SANTA MONICA MOUNTAINS

FIG. 1



MAP OF THE HEAVY MINERAL ZONES OF THE MODELO FORMATION

FIG. 2

FIG. 3. Cut-crop of a shale member in the Modelo formation along Beverly Glen Boulevard near locality 53 a.

of alternating thin strata of sandstone and shale, and not by a gradual change in texture. Crossbedding occurs occasionally. The formation is well stratified and appears to have been deposited in comparatively still water.

In common with many California Recent sediments, the Modelo sandstone is arkosic and its grains are angular (14). Particles as large as 2 mm. in diameter show only slightly the rounding effects of abrasion. Since grains as small as 0.05 mm. may be rounded by stream transportation (7; 19), it is apparent that the material composing the sediments has not been transported a very great dis-

FIG. 4. Cut-crop of a sandstone member in the Modelo formation *along Beverly Glen Boulevard near locality 53 a.*

tance nor has it been reworked many times prior to its deposition as Modelo (1). The presence of feldspar in the Modelo formation is not particularly significant either as an indicator of paleoclimatic conditions or of distance from source. Feldspar is known to have been transported a distance of 600 miles under the adverse conditions of a warm and humid climate (11). Recent work by the writer has shown that in the southern California region, sands that have been transported by an intermittent stream a distance of 50 miles are still angular and very arkosic. Feldspar apparently is more resistant to chemical decomposition and to abrasion than is generally believed.

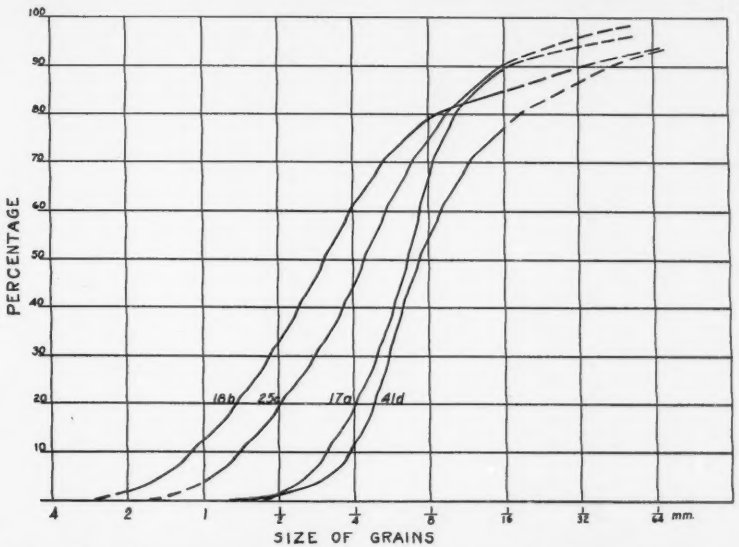


FIG. 5. Cumulative curves, each showing the texture of a sample from a different mineral zone, 17a from zone A, 18b from zone B, 25c from zone C, and 41d from zone D.

The heavy mineral separations were made in the laboratory, using the method described by Milner (12). Observations and comparisons were confined exclusively to material of one grade-size (one-fourth to one-eighth mm.). The advantages of using material of the same grade-size when comparing heavy mineral concentrates have been noted by Dryden and by the writer (2; 4). After identifying the minerals by optical methods, counts were made under the binocular microscope. This procedure was practicable because the various minerals could be distinguished by color, cleavage, shape and magnetic properties. With a few exceptions, the number of grains counted for each sample exceeded 300, which is generally sufficient to insure reasona-

ble accuracy of the mineral percentages (3).

Two histograms have been used to represent the quantitative mineralogical characteristics of each sample. One indicates the relative abundance of each mineral species. The other shows the number of grains of each species that is present in one gram of sand. The latter data are secured by

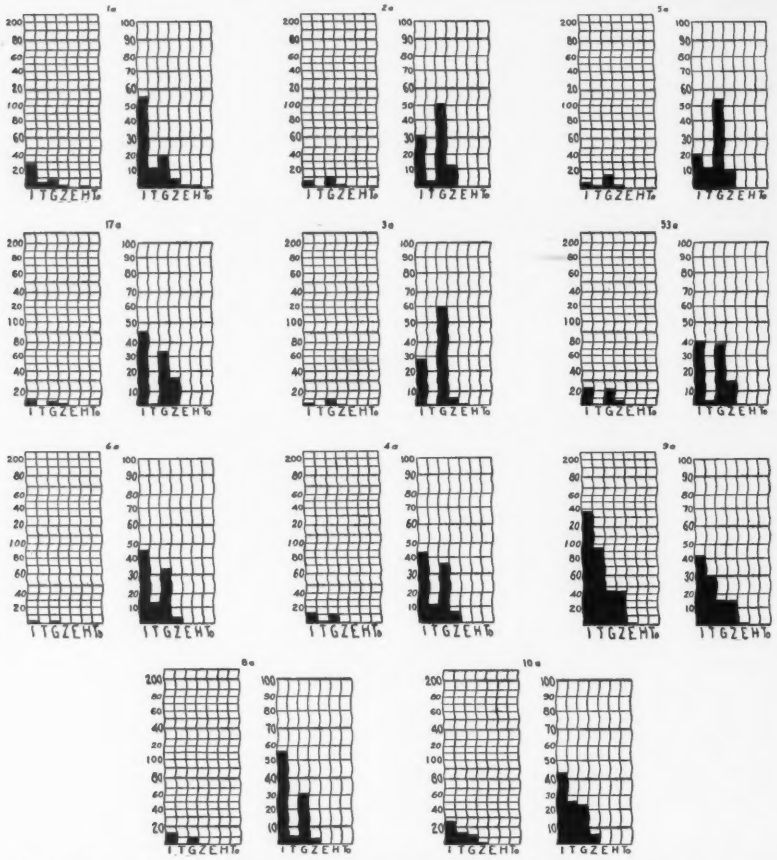


FIG. 6. Zone A., Explanation: I=ilmenite, T=titanite, G=garnet, Z=zircon, E=epidote, *H=hornblende, To=tourmaline. The right histogram of each sample indicates the percentage,* by number of grains, of each mineral species in the size fraction between one-fourth and one-eighth mm. The left histogram of each sample indicates the actual number of grains of any mineral species in one gram of the size fraction between one-fourth and one-eighth mm. Zone A. Epidote, hornblende, and tourmaline are absent or present in only negligible quantity. Ilmenite and garnet are generally more abundant than titanite. (9 a and 10 a are transition samples between zone A and zone B.)

simple calculations.[1] This combination of histograms presents graphically the quantitative relations between the heavy and light mineral fractions as well as between the various species of the heavy residue. A knowledge of the absolute abundance of heavy minerals in a sediment is helpful to a proper interpretation of its geologic history.

The following heavy minerals have been found in the Modelo formation: ilmenite, magnetite, titanite, garnet, epidote, hornblende, tourmaline, zircon, muscovite, biotite, and barite. Little attention was devoted to the barite and the micas because of the authigenic character of the former and the ubiquitous nature of the latter. Ilmenite, as such, was identified on the basis of a positive reaction to a chemical test for titanium and its strong magnetic susceptibility. Mag-

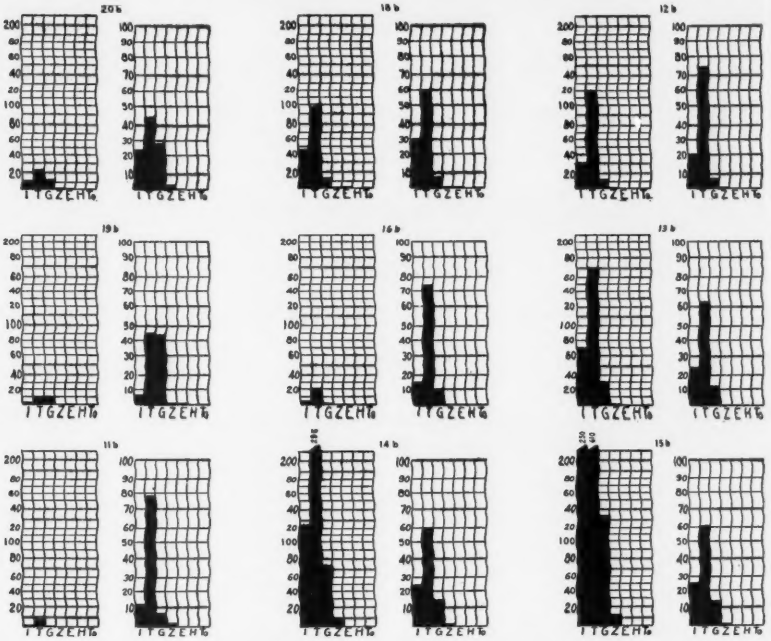


FIG. 7. Zone B. Epidote, hornblende, and tourmaline are absent, or present only in negligible quantity. Titanite is more abundant than either ilmenite or garnet.

[1] Let p = no. of grains of any mineral species per gram of undifferentiated sand ($\frac{1}{4}$–$\frac{1}{8}$ mm.).
f = fraction of total heavy concentrate used for mineral count. (Secured by means of sample splitter.)
n = no. of grains of any mineral species counted.
w = wt. in grams of undifferentiated sand from which heavy concentrate was separated.
Then $p = n/fw$

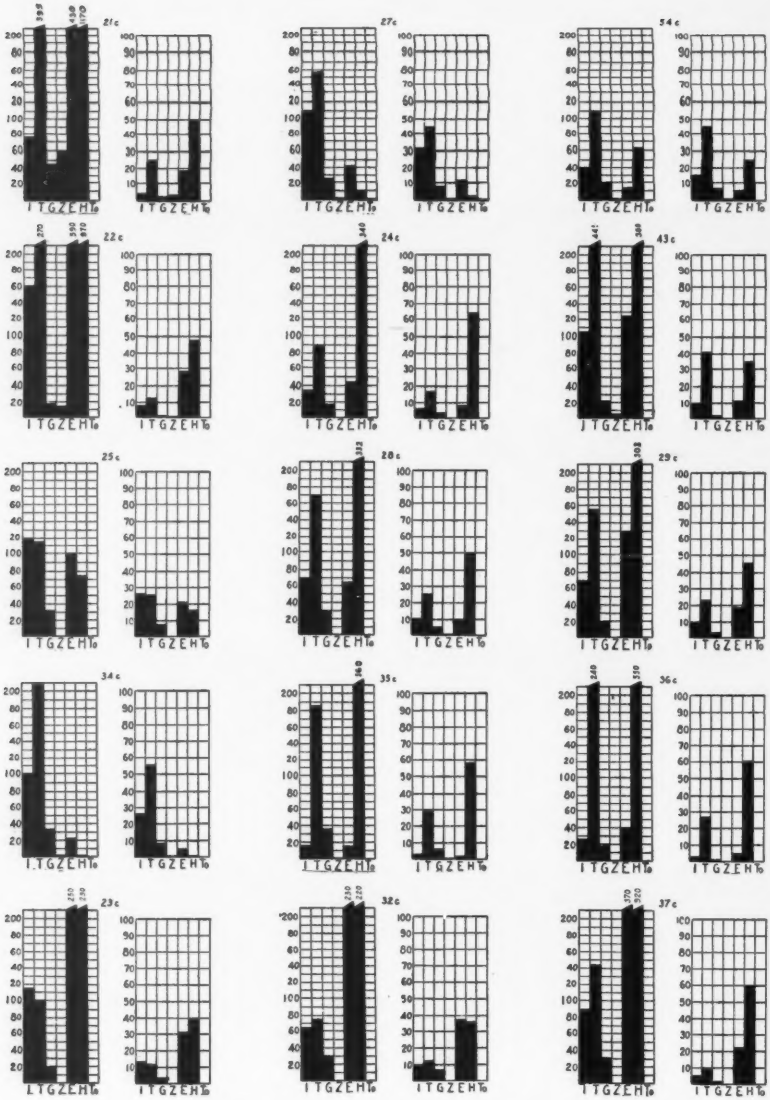


FIG. 8a *(see opposite page for legend)*

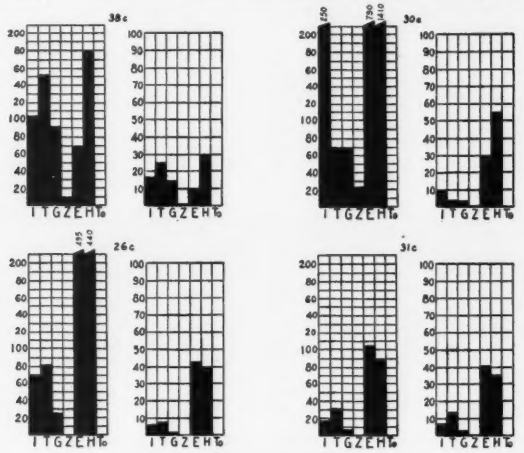
netite was recognized by its exceptionally strong magnetic properties and its octahedral habit. It is not unreasonable to suspect that much of what has been called ilmenite may be titaniferous magnetite.

Ilmenite, titanite, garnet, epidote, hornblende, tourmaline, and zircon are the heavy minerals that were used to zone the Modelo formation. From qualitative and quantitative considerations of the distribution of these minerals, it is possible to definitely distinguish four zones in the lower member of the Modelo formation. This in itself is not unusual. It is remarkable however, that these zones should transect the lithologic boundaries and the structure. This is a feature of utmost significance to those using heavy minerals for the determination of subsurface structures.

The zones were determined in two ways: (1) by the presence or absence of mineral species, (2) by the relative proportions of the various mineral species.

Zone D, the lowest in the Modelo formation, is the least uniform in its mineral content. It is distinguished as a zone largely because it lies between the definitely identifiable zone C above and a non-conformity below. It is characterized in its western part by the presence of tourmaline which is absent or exceedingly rare in the overlying zones and in its eastern part by the ilmenite-titanite-garnet proportions which are distinctly different from those of zone C above. Heavy minerals are not abundant in this zone.

Zone C is distinguished by the presence of hornblende and epidote and the relative proportions of il-



(*See opposite page for first part of figure*)

FIG. 8*a*, *b*. Zone C. Epidote and hornblende are present: very abundant at the base of this zone and diminishing in abundance toward the top. Tourmaline is absent. Titanite is normally more abundant than either ilmenite or garnet.

menite, titanite, and garnet. Heavy minerals are comparatively abundant here.

Hornblende and epidote are absent from zone B but it possesses the same ilmenite-titanite-garnet proportions characteristic of the underlying zone C. The heavy mineral content of the sediments is small.

Hornblende and epidote are also absent from zone A but it may be distinguished from the contiguous zone B by its ilmenite-titanite-garnet proportions. Heavy minerals are scarce, forming less then one-half of one per cent of the sediment.

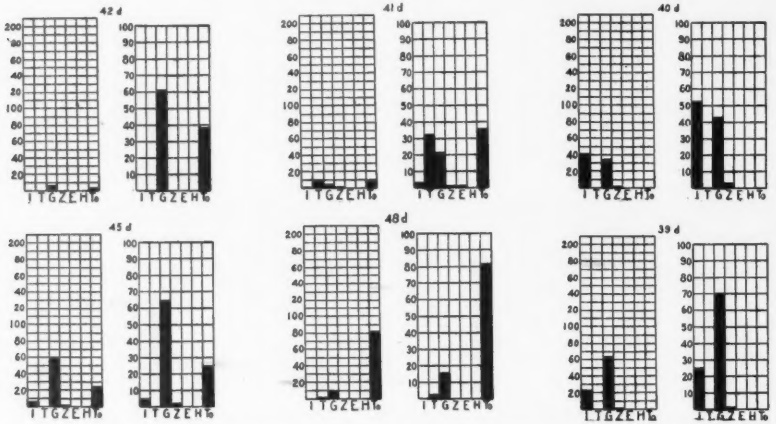


FIG. 9. Zone D. Epidote and hornblende are absent, or present only in negligible quantity. Tourmaline is present in the western part of this zone. Titanite is rare. Garnet is always present and ilmenite is usually present.

Descriptions of heavy mineral zones are not uncommon and their usefulness for correlation, especially where fossils are rare or lacking, has been repeatedly pointed out by sedimentary petrologists (5; 12), but to the writer's knowledge there have been no descriptions heretofore of mineral zones transecting lithologic units.

Many paleontologists are aware that faunal zones sometimes cut across rock units (16; 17). The paleontologist assumes that the character of the included faunal assemblage indicates conclusively the age of the sediments (10). A faunal zone, therefore, consists of material accumulated during an interval of contemporaneous time and a zonal boundary is the equivalent of an isochronal surface. H. G. Schenck, appreciating the full significance of faunal zones transecting lithologic boundaries, stated in a recent article, "No accurate correlations will be possible until time and rock units are separated in the investigator's mind and words, . . ." (16, p. 534).

Faunal zones crossing rock units are easily explained as the conse-

quences of transgressing or regressing seas. Consider as an illustration a basal conglomerate or sandstone being formed by a slowly transgressing sea. It will vary in age from place to place, being younger in the localities where the land has been submerged more recently. If conditions are suitable for the development of a fauna and if the fauna is short-lived compared to the velocity of the landward moving sea, the faunal zones will cross the lithologic boundaries. Figure 10 illustrates the consequences of both transgressing and regressing seas when several strata are involved. It should be observed that for any one lithologic unit, the age becomes progressively younger toward the periphery of the basin if it has been deposited by a transgressing sea, and older toward the periphery when deposited by a regressing sea.

It cannot always be justifiably assumed that mineral zone boundaries are surfaces of contemporaneous deposition. Only when there has been uniform distribution of the sediment carried into a basin is it likely that a mineral zone boundary may represent the locus of points of concurrent deposition.

It is easy to understand why mineral zones may cross chronologic surfaces. Consider a basin receiving sediments from two provinces of widely differing rock types. Currents are too weak to thoroughly mix and distribute the sediments uniformly. As a consequence, the stratum being deposited will not be distinguished by one homogeneous heavy mineral suite but rather by two suites as illustrated by Figure 11, and the mineral zone boundary will be neither parallel nor coincident with the chrono-

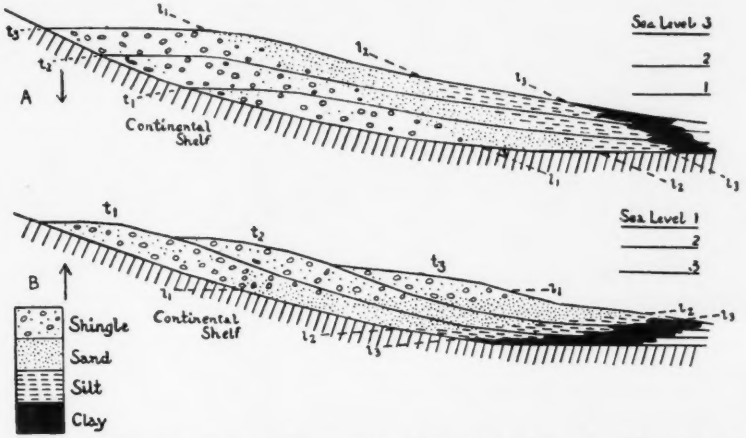


FIG. 10. Diagram to illustrate Transgression of Chronological (t_1-t_3) and Lithological (l_1-l_3) planes: A, Subsiding floor, B Rising floor. (Adapted by the author from the original drawing by Prof. P. G. H. Boswell, *op. cit.*, p. 8.) (From Milner, H. B., Sedimentary Petrography, D. Van Nostrand Co., N. Y., 1929.)

logic surfaces. Increasing the number of sources of sediment and the range in composition of the provenance rocks will increase the complexity of the relations between the mineral zone boundaries and the time surfaces.

In early Modelo time the sea in this district was spreading (8, p. 104). Figure 2 shows each stratigraphically higher sandstone unit overlapping its predecessor. It was to be expected, therefore, that the chronologic surfaces would cut the sandstone units in the same manner as illustrated in Figure 10 for a transgressing sea, and that the mineral zone boundaries, if they represented surfaces of contemporaneous deposition, would do likewise. A careful study of the mineral zone map shows that as the margins of the trough are approached, each successive mineral zone that cuts across a sandstone unit is usually stratigraphically lower than the one preceding. If the mineral zone boundaries are identical to chronologic surfaces, then the sequence of the transections in the Modelo is like that resulting from a regressing sea as illustrated in Figure 10. Since structural evidence points to a spreading sea during early Modelo time, the boundary relations that exist here between the lithologic units and the mineral zones present an anomaly. Whether or not the mineral zone boundaries are loci of points of concurrent deposition and therefore chronologic surfaces remains a moot question.

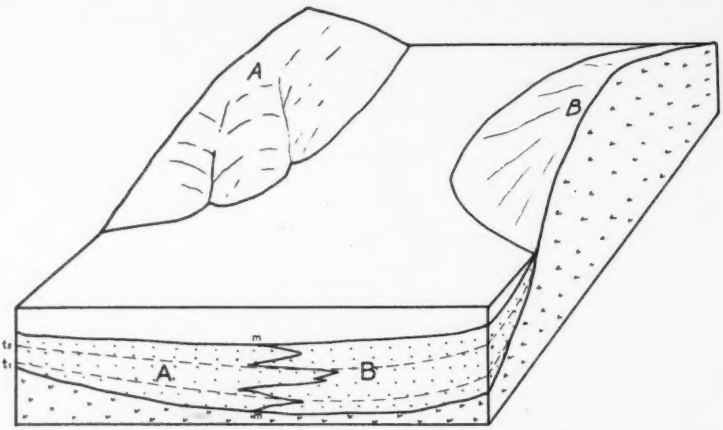


FIG. 11. Illustrating a mineral zone boundary m–m transecting chronologic planes t_1, t_2. This type of boundary relation may occur where detritus from two different rock provinces is being swept into a basin where the currents are too weak to thoroughly mix the incoming detritus.

This investigation shows that there are distinct variations of the heavy minerals both vertically and laterally in the Modelo formation of this district. Although vertical variations

were anticipated and are desirable for zoning purposes, the rapid lateral variations within some of the sandstone units were entirely unexpected.

The value of this investigation lies in the fact that data have been gathered which disclose some of the difficulties that may be encountered when heavy minerals are employed for zoning and structural determinations. The writer is not of the opinion that heavy minerals are invariably useless for correlation. In basins where currents have produced a uniform mixture and distribution of the incoming detritus, the likelihood of securing useful data from heavy mineral studies is good. No better argument favoring the use of heavy minerals as criteria for correlation can be given than the fact that they have been employed with success in the oil fields of the Mid-Continent, in Texas, and in other regions (6; 9; 15; 18). More work of a detailed nature will have to be done in California before their usefulness in this section can be adequately judged.

The writer is grateful to Dr. Ian Campbell of the California Institute of Technology for the encouragement and helpful suggestions tendered during the progress of this investigation and the writing of this report.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 1, PP. 16–22, FIGS. 1–3,
APRIL, 1936

DOMINANT FACTORS IN THE FORMATION OF FIRM AND SOFT SAND BEACHES*

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Geological Survey of Canada, Ottawa, Canada

ABSTRACT

Sand beaches differ widely with respect to their firmness or hardness. On some beaches walking is tiresome and motoring impossible; while others are ideal speedways owing to the stone-like hardness of the sand. A sea beach which presents within the distance of a fraction of a mile the possible extremes of firmness and lack of firmness and various intermediate degrees of hardness is described in detail. The factors responsible for the great contrasts in sand structure represented by these differences are pointed out and demonstrated by experiments. The conclusion is reached that the close-packed and loose-packed structures responsible for firm and soft sands may under favorable conditions be perpetuated in the sandstones resulting from the eventual consolidation of beach and bar sands and have considerable economic importance.

The impression appears to be widespread that the sands of sea beaches are nearly everywhere sufficiently soft and yielding to record footprints. This common opinion is well reflected in Longfellow's lines:

"The little waves with their soft white hands,
Efface the footprints in the sands."

Professor N. S. Shaler who had a wide knowledge of the south Atlantic coast beaches, speaks only of the yielding sands.

> The grains of ever-shifting sand are so incoherent that the foot sinks deep into the mass and the unequal position of the feet racks the walker in a painful way. I remember a walk of sixty miles along this shore, from Biscayne Bay to Jupiter inlet, as among the most trying incidents in my field experience (1).

The truth is that beaches with sand so firm that it fails to take footprints are common features of both sea and lake shores. On many beaches the human foot leaves scarcely a trace. The compactness of the sand on some of the Atlantic beaches in the Southern states is such that at low tide they are extensively used for automobile driving. The beach at Daytona, Florida, is widely known as a racing beach. On such beaches the wheels of a car leave ordinarily no impression beyond a faint suggestion of the pattern of the tire. It must be added, however, that the incautious driver who assumes the whole width of the beach to be everywhere firm, may in turning find his front tires buried in sand, while the rear wheels remain on a surface almost as firm as that of sandstone. South Beach, St. Augustine, Florida, is a representative example of the beaches of the

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South Atlantic States. At low tide it displays a belt of fine white quartz sand (2) very gently inclined seaward and backed by low sand dunes rising 8 or 10 feet above high tide level. The sand grains are very small, 90 per cent being 2 mm. or less in diameter. The following mechanical analysis (3) indicates the character of the sand at South Beach, St. Augustine, as compared with the beach sands 35 miles north of St. Augustine.

Mechanical analyses of two sand samples from Florida beaches

	Plus 0.25 mm. %	0.25/ 0.2 mm. %	0.2/0.1 mm. %	minus 0.1 mm. %
St. Augustine Beach	trace	10	88	2
Atlantic Beach	trace	35	60	5

According to the sand-grading classification adopted by the American Foundrymen's Association for foundry sands in general this sand would be placed in the angular class. Only a small percentage would fall in the subangular class which lies between the angular and rounded grain classes (4).

The most surprising thing about these intertidal beaches for the geologist as for the motor driver is the abruptness of the transition from firm to soft sand, which one encounters in certain localities. A good example of such contrasts on an English beach at Skegness has been cited by the writer (5).

During the summer of 1934, various Atlantic coast beaches south of Virginia were examined with the object of getting some clue to the reasons for the contrasts—often abrupt—in firmness of the sand, which on some beaches is much more pronounced than on others.

The St. Augustine Beach on the east side of Anastasia Island, known as South Beach, differs from Myrtle Beach, S. C., Atlantic Beach, north Florida and other beaches studied, in having a beach which, though exposed to the full force of the Atlantic surf, terminates on the north in a spit. The two sides of this spit thus display two beaches at low tide, one protected, the other unprotected from Atlantic breakers. The small salt water lakelet with drainage outlet near the base of this spit, exposed at low tide on the lagoon side, indicates plainly the complexity and rotating character of the tidal currents on the inner border of the spit (fig. 1). These swirling currents, which are active at certain stages of tide, have excavated a nearly circular salt water pond at the base of the intertidal spit and are able to prevent the Atlantic surges from obliterating it with the sand which surrounds it. The contrasted conditions of deposition existing on the two sides of the spit are reflected in the relative firmness of the sand on the east and west sides.

Footprints of the observer in crossing the base of the spit forming the northern terminus of South Beach at low tide afford a convenient record of the contrasts in firmness which different parts of the beach section display. In making a paced traverse during ebb tide across the spit, the depths of the footprints made on it

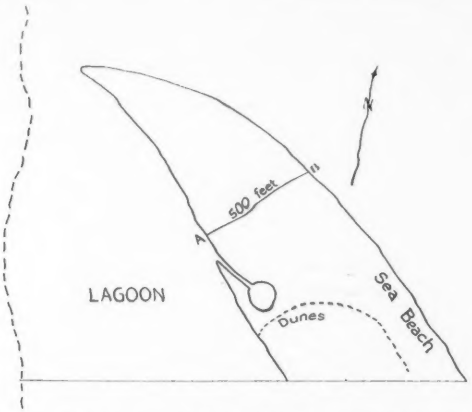
were noted and recorded as follows:

From water's edge on lagoon side to surf line on ocean side, the record is:

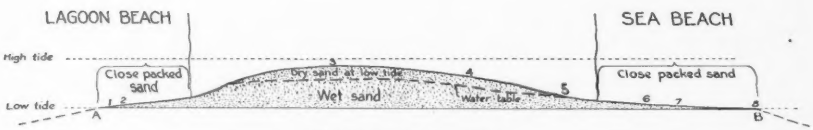
	Feet
1. *Firm wet sand* with small mud lumps near water *No footprints*	26
2. *Soft, nearly dry sand* Distinct footprints	23
3. *Very soft sand* Footprints 1 to 6 inches deep at the heel	163
4. *Soft sand* Footprints one-fourth to one-half inch deep; sand mostly current rippled.	91
5. *Soft sand* Footprints 1 inch deep	65
6. *Soft sand* Footprints one-half inch deep	49
7. *Sand firmer*	20
8. *Very firm wet sand* No footprints.	62

The last four records are on the sea slope, number 4 on a nearly level area while number 3 includes an abrupt change of slope and rapid drying conditions.

Here we have in the same beach cross section, sand, which toward *the ends shows a degree of compact*ness that prevents it from recording *footprints, while in some other parts*



Sketch map of beach and spit at low tide.
South Beach.
ANASTASIA ISLAND, FLORIDA.



Diagrammatic Section
across South Beach sand spit
ANASTASIA ISLAND
at low tide.

FIG. 1. Diagrammatic section of sand spit beach at St. Augustine.

of it the pedestrian may sink to a depth of 4 inches or more. Water content and degree of expulsion of air from sand are the factors chiefly responsible for these considerable differences in firmness and these depend upon elevation above low tide level and slope of beach. Consideration of the conditions developed experimentally in sand during the expulsion of air from it will make this fact plain.

In dry sand the interstices between the grains are filled with air which permits the grains to move freely under pressure one against another. Where water in limited quantity replaces the air, adjacent sand grains are drawn together by the force of capillarity. Under the grip of this force incoherent dry sand when water replaces the air, immediately assumes some of the characteristics of a solid. Complete saturation and flooding of the surface of the wet sand, however, breaks the hold of capillarity on the sand which then again becomes nearly as incoherent as when dry. If a two-inch wire nail is dropped from a height of six inches on two samples of fine sand, one saturated with water, the other dry, the penetration of the nail in the dry sand will be four or five times greater than in the wet sand.

Perhaps the most puzzling beach feature to explain is the occurrence adjacent to zones of hard sand, of patches of extremely soft sand, such as were found in the traverse shown above where the footprints reached a depth of four or five inches at times. These soft patches apparently always occur in the higher parts of the intertidal beach where the sand is longest exposed to air and sun. The consequent, nearly complete drying of the upper layers of such sands and the substitution of air for water in the interspaces between the sand grains, leaves them subject to the rapid expulsion of the air near the flood tide period. This air expulsion process is sometimes associated with some agitation of the sand and water. Cornish in recording his observation on this feature of the rising tide in the estuary of the Severn river, states that "The sands which had been drying for several hours, were covered so suddenly that the imprisoned air spouted through the seething water" (6). The escape of air from sand at the mouth of the Avon river, N. S., as the tide rises has been described as follows: "The phenomenon which apparently happens at very irregular intervals, has been observed twice by the writer. In one case where the opportunity to observe it at close quarters was excellent, the bubbling was of a rather violent character comparable with that which accompanies the boiling of water, and extended over several square feet of surface. In this case the effervescence occurred in shallow water which was covering a sand-bar and continued for several minutes" (7). While much of the air is certain to be driven out of the sand of the upper beach as it is submerged by the flow, some of it may be trapped and remain in patches of the upper beach and greatly modify its texture and firmness (see Figs. 2 and 3).

Partial expulsion of air from dry sand by encroaching water moving downwards, and the consequent effect of the air which remains imprisoned on the texture of the sand can be easily observed in a glass jar of dry sand after adding water at the top. Penetration of the sand by water acting through both gravity and capillary attraction results after air zones or cavities forcing the wet and dry masses apart and lifting the former as in Figure 2A, B, C. Essentially the same porous sand structure as shown in Figure 2B may be produced in the upper beach near the end of the flow tide by the joint action of surf and rising tide. The swash from the breakers rolling in upon the beach may wet-blanket the

FIG. 2. Shows porosity and air spaces developed in dry sand through segregation of included air by addition of water at top of containers. Relatively small amounts of water have been added to A and C leaving in A the wet and dry sand separated by an air space. In C irregular penetration of water has produced a zigzag air zone and exit while in B rather uniform porosity has developed throughout.

the water has saturated the upper portion in the development of air pressure within the sand. This pressure is produced under the propulsion of capillarity. Some of the imprisoned air driven out of the upper dry sand escapes upward through the wet sand as bubbles, but much of it held below the close packed wet layer develops numerous small air pockets and may accumulate in one or more top of a zone of dry sand, preventing the escape of much of the air which a rising tide imprisons and causing it to give to the sand a structure comparable to that which leaven impresses on wet flour. The contrast in the uniform close packed structure resulting from the rise of water through sand from below, and the porous structure with air spaces produced by tidal overflow on dry sand

is suggested by the experiments shown in Fig. 3.

The net result of the encircling flood tide covering the intertidal sand spit at South Beach is the development in the upper part of the beach at flood tide of a special phase of beach structure in the completely dry sand which leaves the sand honeycombed with minute pockets of imprisoned air. This belt of soft sand beach in the median zone of the spit has always a shorter period of exposure than the lower levels of the beach to the heavy surf which commonly pounds them for hours eliminating every trace of air. The shorter exposure of the upper beach under average conditions will permit retention in it of a larger amount of air than is possible in the lower beach. Where the gradient of the beach is low the close-packed sand structure associated with one stage of water saturation and complete expulsion of the air is never lost in a wide zone next the sea. A steep gradient by favoring drainage and drying produces and perpetuates an open packed yielding beach.

It might be assumed *a priori* that the rise of the water in beach sand would keep pace with the rise of the tide but experimental observations on a sand-filled tube[1] when water is introduced at the base show that the water table rises very slowly and lags far behind the rate of upward movement of the flow tide. The flow of the tide would therefore always cover the higher levels of the surface of the intertidal zone in advance of the rise of the water table to the surface and imprison sufficient air in the sand of the upper beach to leave it with a loose packed structure. The close packed structure which accompanies the absorption of a certain amount of water by capillarity and expulsion of air results in a drawing together of the sand grains and some reduction in bulk. This gives rise to the remark-

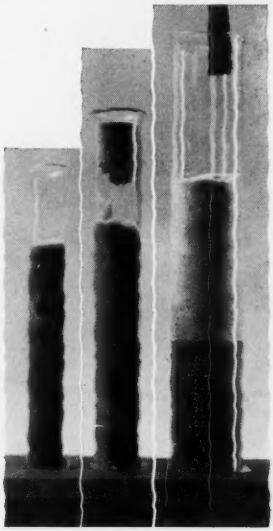


FIG. 3. Shows contrasted types of sand structure developed by permitting sand to absorb water from the top and from the bottom. Note air spaces in left-hand tubes and close packed dark sand without air spaces in lower half of large tube which has received water from bottom only.

[1] A glass tube 62 inches long and 2¼ inches in diameter filled with sand to a height of 58 inches was connected by a ¼-inch rubber tube with a water supply having a head kept 10 to 15 inches above the position of the water table as it slowly moved upward from the gauze covered end of tubing at bottom of sand column. The water table moved upward so slowly that it would be negligible as compared with the upward movement of a rising tide.

ably firm beaches of the South Atlantic coast where the gradient is too low to facilitate drying during the ebb.

The presence of a considerable percentage of shell fragments in sand or a large size of sand grain are factors which would reduce the effective operation of the binding influence of capillarity and prevent the development of a hard beach. The influence of grain size is illustrated by the beaches on the east and west sides of Pelee Island in Lake Erie. The east shore has a beach composed of very fine sand as firm as some of the Florida beaches, whereas on the west shore beach, the very coarse sand is nowhere very firm.

Operation of the essential factors or conditions which conspire to produce from sand of uniform type hard and compact beach zones adjacent to belts of incoherent sand with porous texture, may under certain favorable conditions leave their definite imprint on the sandstones into which beach sands are transmuted in the ordinary course of geological history. When such favorable conditions happen to work together for preservation as sandstone, of belts of sand made porous by air trapped at high tide and buried permanently by exceptional storms, the structure for a highly porous sandstone has been prepared. Such a sandstone should be a potential oil or gas reservoir or a bed in which free circulation of water may develop concretions elsewhere unknown in the formation. The conditions are shown in Figure 1 under which such open-textured sandstones could be developed. These would give them an orientation parallel with the coast lines of their natal seas.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 1, PP. 23–27, FIG. 1, TABLES I–III,
APRIL, 1936

NOTES ON THE DIELECTRIC SEPARATION OF MINERAL GRAINS

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ABSTRACT

Experiments dealing with the dielectric separation of mineral grains indicate that the best results may be obtained by using ordinary 60-cycle alternating current stepped up to 880 volts. Furfural and benzene, mixed in varying proportions, supply the most satisfactory media. Grains of a given mineral may be separated quite effectively from others that have a distinctly higher or lower dielectric constant. The dielectric constants of 38 minerals determined in the above media are tabulated.

Recent experiments involving the sorting of mineral grains by means of dielectric separation have convinced the writer that the dielectric methods which have been suggested to date do not give results compatible with the published dielectric constants of many minerals. The following data, compiled by modifying slightly the technique of separation, are submitted, therefore, to serve as a guide to further studies of the method.

Dielectric separation was first applied by Hatfield (1) in the commercial separation of cassiterite from quartz gangue. Suggestions for the laboratory modification of the technique have been published by Holman and Shepherd (2) and by Tickell (3).

The separation is based on the principle that two oppositely charged poles attract each other with a force that varies inversely as the square of the distance between them. The force with which the poles are attracted is diminished considerably if the dissimilar charges are placed in a medium which is non-conducting, *i.e.*, a dielectric medium. The force in attraction varies for different media (liquid media in this application), and the ratio of the attraction in a vacuum as compared with the ratio in a given medium is termed the *dielectric constant* of that medium. Any foreign substance in a medium of a given dielectric will be attracted to the electric field between the poles if it possesses a dielectric constant greater than the medium.

The experiments of Hatfield, Holman and Shepherd were carried out with an alteranting current of 250 volts and 100 cycles. Tickell finds that ordinary 60-cycle current transformed up to 300 or 400 volts is preferable in that it does not require a source of direct current or a commutator to supply the higher frequency. Experiments conducted by the writer with 440 volts proved rather unsatisfactory because the mineral grains were not attracted to the

electric field with sufficient intensity to allow their removal from the medium. For this reason, the current was stepped up to 880 volts. This increased voltage yielded more satisfactory results.

The 880 voltage is secured by using an ordinary radio transformer hooked up in the manner shown by Figure 1.

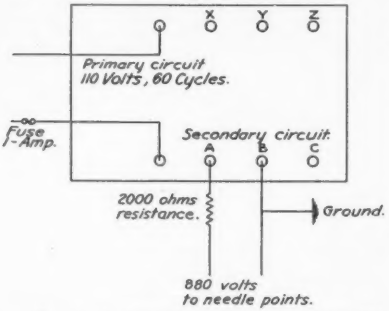

FIG. 1. Hookup of transformer yielding 880 volts. AC yields 880 volts, AB and BC yield 440 volts. X, Y, and Z may be used to provide a small pilot light.

A 1-ampere fuse is placed in the primary circuit, and a resistance of 2000 ohms in the secondary circuit. Wires from the secondary circuit lead to needles mounted on an insulated pencil-like handle. The space between the needle points serves as the electric field needed for the separation.

The dielectric constants of some of the more common liquids are listed in Table I. Most of these liquids have been tested by the writer. Acetic acid, amyl alcohol, ethyl alcohol, and methyl alcohol, proved unsatisfactory because destructive arcing occurred between the needle points when they were used. Bromoform is of little value because of its high specific gravity, and the reasons for the inadaptability of chloroform are of course obvious. Media with dielectric constants ranging from 2 to 36, prepared by mixing nitrobenzine and kerosene in varying proportions,[1] have proved satisfactory, though objection to nitrobenzine may be raised because of its toxic nature.

TABLE I. *The dielectric constants of several liquids at 20°C.*

Liquid	Dielectric Constant
Acetic acid	6.4
Amyl alcohol	15.8
Benzene	2.28
Bromoform	4.5
Carbon tetrachloride	2.24
Chloroform	5.2
Ethyl alcohol	25.7
Furfural	42.0
Kerosene	2.0
Methyl alcohol	33.7
Nitrobenzene	36.0
Water	80.0

On this ground, Tickell suggests the use of furfural in preference to nitrobenzene. However, furfural and kerosene are immiscible; therefore, it is necessary to replace kerosene with another liquid of low dielectric constant. Benzene (as distinct from benzine) appears to be the most satisfactory substitute. Media prepared by the mixture of furfural and benzene range in dielectric constants from 2.28 to 42, and in general yielded the best results.[2]

[1] For example, one part of nitrobenzine (K equal to 36) and five parts of kerosene (K equal to 2) would yield a resulting medium with a dielectric constant of 7.7.

[2] Furfural, though relatively inexpensive, is difficult to obtain in a pure state. It is quite unstable; within several months after distillation it becomes badly discolored, and a fluffy precipitate begins to form. When ordering the liquid, the writer has found it necessary to emphasize that a *colorless*, chemically pure product was desired.

For prolonged work with the liquids, it may be desirable to have a small fan situated a few feet from the apparatus with the breeze directed in such a manner as to carry the vapors away from the worker.

A word of caution may be added here. Benzene is highly inflammable and it is necessary first to remove magnetically such good electrical conductors as magnetite and ilmenite. Arcing produced by the presence of these minerals may cause the liquid to ignite.

The procedure followed by the writer differs only slightly from that described by Tickell. The separation is performed in a small, flat, glass container. The mineral grains to be sorted are treated first by a magnet to remove the highly magnetic grains, and then placed in the container. Furfural and benzene are drawn from burettes in the proportions necessary to obtain a liquid medium of the desired dielectric constant, and the needle points immersed in the liquid. The electric field between the needle points (which are placed about 1 mm. apart) attracts the grains with a dielectric constant higher than the liquid medium, and repels those with lower constants. The grains attracted to the points may be transferred to a smaller glass dish placed in the larger container, the needle points being held in the liquid above the smaller dish and then raised above the surface of the liquid. When the needles are raised above the liquid, the grains fall from the needle points into the smaller dish. This dish may then be removed with forceps and the mineral grains washed with alcohol and collected on filter paper.

Following this procedure, the dielectric constants of a number of minerals were experimentally determined. However, the technique was modified slightly for these determinations in that standard sets of liquids were used throughout, and the dielectric constants of the minerals were determined as being between two sets, *i.e.*, between 4 and 5, etc. The liquids were mixed in comparatively large amounts, thus assuring media of uniform constants. The mineral grains were obtained by crushing laboratory samples to pass a 100-mesh screen. The grains were placed in the container, covered by a liquid of known dielectric constant, and the needle points passed among the grains. The grains which were attracted to the points with sufficient force to allow their separation and removal from the main mass were considered to have a dielectric constant greater than the liquid medium; those that were not attracted had constants lower than the medium.

The dielectric constants of the minerals tested by the writer are listed in Table II. It will be noted that there is a decided disagreement between these constants experimentally derived and the maximum dielectric constants of several minerals listed in the *International Critical Tables* and found in Table III of this paper. The reason for this difference is not clear to the writer, though it is possible that experiments employing frequencies greater than the 60-cycle frequency used in these tests might

TABLE II. *Dielectric constants of mineral grains. Measured with alternating current, 60-cycle frequency and 880 volts.*

Mineral	Dielectric Constant
Glauconite	14–15
Opal	8–9
Biotite, Fe	6–7
Actinolite	5–6
Augite	5–6
Biotite, Mg	5–6
Chlorite	5–6
Epidote	5–6
Kaolinite	5–6
Monozite	5–6
Sphalerite	5–6
Cyanite	4–5
Gypsum	4–5
Hornblende	4–5
Sillimanite	4–5
Titanite	4–5
Albite	3.5–4
Anorthite	3.5–4
Apatite	3.5–4
Barite	3.5–4
Cerussite	3.5–4
Corundum	3.5–4
Diopside	3.5–4
Dolomite	3.5–4
Fluorite	3.5–4
Garnet	3.5–4
Halite	3.5–4
Nephelite	3.5–4
Olivine	3.5–4
Orthoclase	3.5–4
Siderite	3.5–4
Spodumene	3.5–4
Staurolite	3.5–4
Tourmaline	3.5–4
Wollastonite	3.5–4
Andalusite	3–3.5
Calcite	3–3.5
Quartz	3–3.5

produce results more compatible with those already published. The dielectric constant will, of course, vary with the crystallographic position of the mineral in the electric field and with increase in size of the particle, but such variance would not entirely account for the difference in the two tables. The disagreement probably can be explained in part by the fact that the reported dielectric constants are the maxima, not the average constants.

The fact that so many minerals have constants within a relatively small range may limit the application of this method of separation. However, there are several uses in which it is distinctly valuable. For example, a given mineral may be separated quite effectively from another that has a distinctly higher or lower dielectric constant. This can be accomplished by gradually lowering the dielectric constant of the medium until one of the minerals can be removed. The writer has recently separated glauconite grains from a number of sandstones, and in each in-

TABLE III. *Maximum dielectric constants of several minerals as reported in* International Critical Tables.

Mineral	Dielectric Constant
Adularia	6.2
Analcite	6.7
Anhydrite	6.3
Apatite	10.5
Aragonite	10.5
Augite	10.7
Barite	12.2
Beryl	7.8
Calcite	8.5
Cassiterite	24.0
Celestite	18.5
Cerussite	26.3
Chalcedony	4.2
Corundum	13.1
Diamond	5.5
Fluorite	6.8
Gypsum	11.6
Halite	6.2
Quartz	5.0
Rutile	78.0
Smithsonite	9.4
Strontianite	6.6
Topaz	7.6
Tourmaline	7.1
Vesuvianite	9.2
Witherite	7.8
Wurtzite	8.2
Zircon	12.0

stance an excellent separation was made possible by this technique. The method has been used successfully also in the removal of impurities from a given mineral.

In the experiments performed by the writer, one baffling feature was noted. This was the fact that the time of immersion had an effect on the constants of several minerals. This was especially noticeable in glauconite. When the mineral was first placed in the liquid it had a constant of 14–15; after it had been immersed about five minutes the constant dropped several points for most of the glauconite grains, though some of them were not affected. The time of immersion did not seem to have such effect on the minerals of lower dielectric constants, possibly because the relative change would not be so noticeable. No attempt was made to determine the exact relation between the time of immersion and the effect on the constants of the minerals.

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BARITE CONCRETIONS FROM THE YAZOO CLAY, EOCENE, OF LOUISIANA[1]

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ABSTRACT

Concretions of aggregates of pisolites composed of 95.6 per cent barium sulfate are recorded from the Yazoo clay, Jackson Eocene, sec. 11., T. 12 N., R. 2 E., Caldwell Parish, Louisiana.

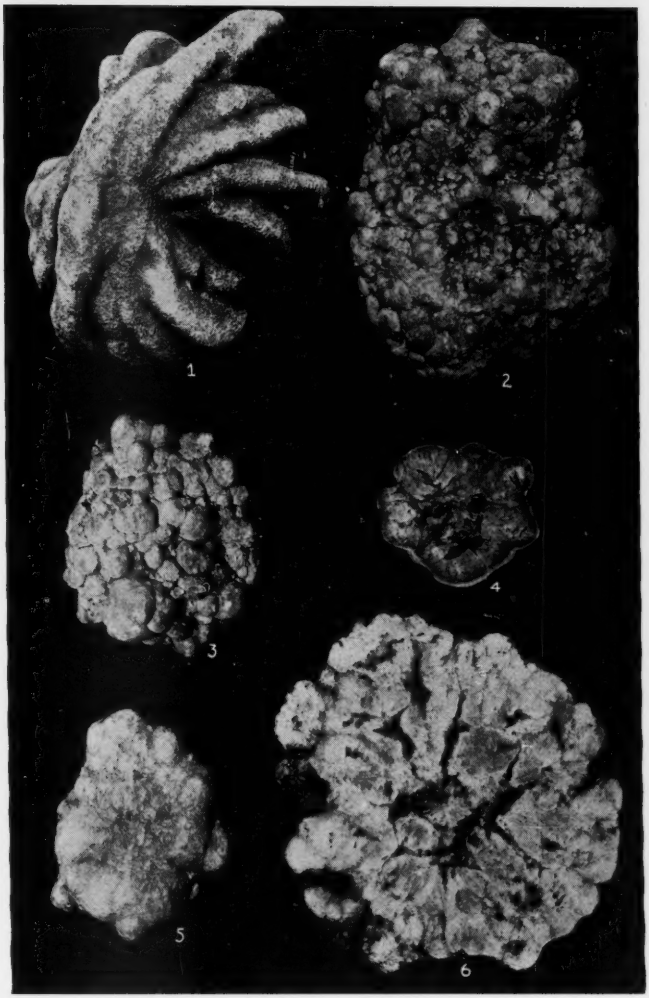
During two visits to Gibson's Landing on the Ouachita River, sec. 11, T. 12. N., R. 2 E., Caldwell Parish, Louisiana, the writer was impressed by the number of white to light-gray concretions of heavy specific gravity in the Yazoo clay of Jackson, upper Eocene age. Many concretions of similar appearance had been noted at other outcrops, but none, as far as could be remembered, were as heavy. Since the first visit concretions of this general appearance have been collected at different places in Louisiana and Mississippi, but only those from Gibson's Landing have been found to be composed of barium sulfate. However, no other collections have been made from the lower part of the Yazoo clay at other localities.

The concretions are light-gray to light-buff in color, depending on the amount of iron stain, but are generally light-gray on freshly broken surfaces. They range to a maximum size of from 4 to 5 inches in diameter, and are composed of aggregates of pisolites varying in size up to one-half an inch or more in diameter. For the most part the individual pisolites are less than one-quarter of an inch in diameter. The surface is finely granular. In section each pisolite has a radiating fibrous texture. The center may or may not be hollow. In massive section these concretions show an intergrowth of the fibrous texture. All of the hollow concretions broken show drusy irregular cavities which are free of foreign material. As far as noted very little foreign material is occluded. The following analysis[2] shows the purity of the material: barium sulfate, 95.6 per cent, other metal sulfates (as sulfates), 2.2 per cent, moisture, 0.1 per cent.

Associated with the barite concretions are many other concretions, which have the same general appearance but are composed of calcium carbonate rather than barium sulfate.

[1] *Published with permission of the Gulf Production Company.*

[2] Analysis by F. W. Karl and H. O. Nicholas, Gulf Production Company.



EXPLANATION OF PLATE 1

FIG. 1. "Petrified Rose" or "Barite Rose" from the Red Beds (Permian) *series six miles east of Norman, Oklahoma. Magnification about 0.8×.*

FIG. 2–5. Barite concretions from the Yazoo Clay, sec. 11, T. 12 N., R. 2 E., Caldwell Parish, Louisiana. Magnification about natural size.

FIG. 6. Barite concretion from same locality as figures 2–5. Magnification 1.77×.

In section texture the calcium carbonate concretions are finely granular rather than radiating fibrous. They are cavernous as are those composed of barium sulfate. Their specific gravity, is, of course, very much less.

Lime concretions similar to those associated with the barium sulfate ones at Gibson's Landing are common at outcrops in Louisiana and Mississippi, but so far no other barite concretions have been noted in these outcrops.

The barite concretions from Gibson's Landing are very different from most of the barite found in the caprock (1) of the Gulf Coast Salt Domes. Some of the salt dome barite is slightly fibrous (2), but not pisolitic. The oolitic barite (2, pl. 9, fig. 5) from Batson Dome, Hardin County, Texas is very different.

The "Petrified Roses" or "Barite Roses" from the Permian of Oklahoma, as shown in Plate 1, Figure 1, are not pisolitic. They contain a much greater amount of foreign material as shown by the following analysis (3):

Analysis of Barite Roses from Oklahoma

	Per cent
Silica dioxide (SiO_2)	45.20
Aluminium oxide (Al_2O_3)	0.86
Iron oxide (Fe_2O_3)	0.93
Water (H_2O)	0.36
Sulphur trioxide (SO_4)	18.15
Barium oxide (BaO)	*34.50*

Hatch and Rastall stated,

> In the case where the cemented masses are spheroidal, the washing away of the uncemented sand causes an accumulation of pebble-like bodies liable to confusion with pebble-beds, as has been the case near Nottingham (4).

No such concentration as this was found at Gibson's Landing.

An excellent discussion of the occurrence of sedimentary deposits of barium minerals was given by Twenhofel (5) in which he mentioned various types of occurrence including pisolites. He cited the oolites and pisolites from Batson and Saratoga oil fields, Hardin County, Texas.

No definite information was obtained which might lead to a conclusion regarding the origin of the barite concretions found at Gibson's Landing. The enclosing material is a fairly homogeneous limy clay or marl. The concretions appear to be more abundant in the lower part of the Yazoo clay, which is underlain at this point by the Moody's Branch marl. The Moody's Branch marl is a fairly porous glauconitic marly sand, and has a thickness of about 27 feet. This in turn is underlain by the impervious clays of the Claiborne.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 1, PP. 31–34, FIGS. 1–3,
APRIL, 1936

MINERAL STUDY OF KIAMICHI FORMATION OF WEST TEXAS

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ABSTRACT

The minerals of Kiamichi formation consist of magnetite, tourmaline, garnet, quartz, pyrite, glauconite and iron oxide. The character and type of the sediments suggest that the materials were derived from a region of average or low relief.

A study of the Kiamichi formation was undertaken to determine the characteristic minerals. It was hoped that the texture of the materials, type and character of the minerals would give some information as to the condition of sedimentation.

The writer wishes to acknowledge the assistance of Mr. A. C. Stults, a graduate student in Geology, in the collection and preparation of the samples. He also aided in the identification of the minerals.

The Kiamichi formation is of Comanchean age and is exposed in the deeper lakes of Lynn and Lamb counties. The formation is about 90 feet thick and consists primarily of shales with interbedded sandstones and limestones. The shales are calcareous blue-gray in color, thinly laminated and friable when dry. The minerals of the shales are angular, consist chiefly of quartz and are smaller than 1/32 mm. in diameter. The sandstones are cross-laminated, have yellow to brown colors, are cemented with calcareous material and the beds range in thickness from 1 to 12 inches. Of the two most conspicuous sandstones one is located about midway in the formation and the second is near the top. The one near the middle is compact and may be identified by its platy structure. The upper sandstone is fossiliferous and contains iron nodules. The limestones are compact, have a light gray color, are discontinuous and range in thickness from 3 to 12 inches. Most of the limestone layers are fossiliferous.

MINERALS OF KIAMICHI

The minerals composing the Kiamichi formation are described in the paragraphs that follow.

Quartz. The majority of the quartz is subangular with a few of the larger grains subrounded. The broken minerals exhibit conchoidal fracture. Some of the quartz is iron stained but on the whole it is clear and free of inclusions.

Glauconite. Glauconite is found in particles smaller than 1/16 mm. in

diameter. The grains are irregular, light-green to greenish-brown in color and abundant in the upper part of the formation. The mineral occurs both in the heavy and light fractions. The nucleus of the light particles consist of micro-organisms.

Mica. Flakes of muscovite and biotite are present with the former in greater abundance. These minerals are rare in the clays and finer sediments. The muscovite is clear and found only among the minerals of low specific gravity. The biotite has

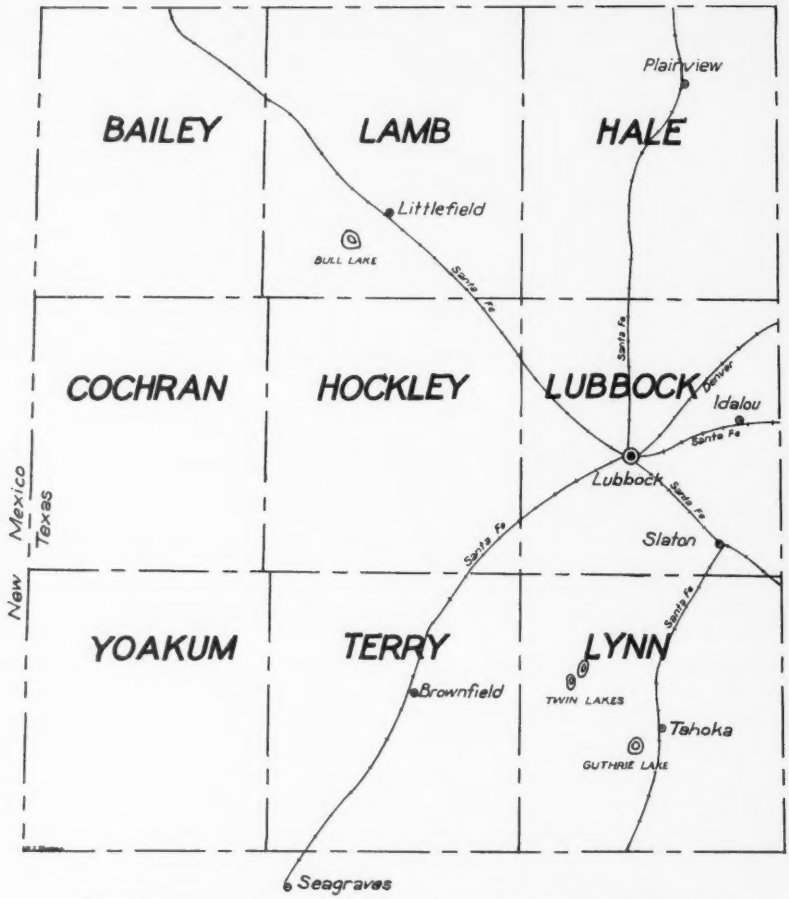

FIG. 1. The Kiamichi is exposed at Guthrie Lake, Twin Lakes and Bull Lake.

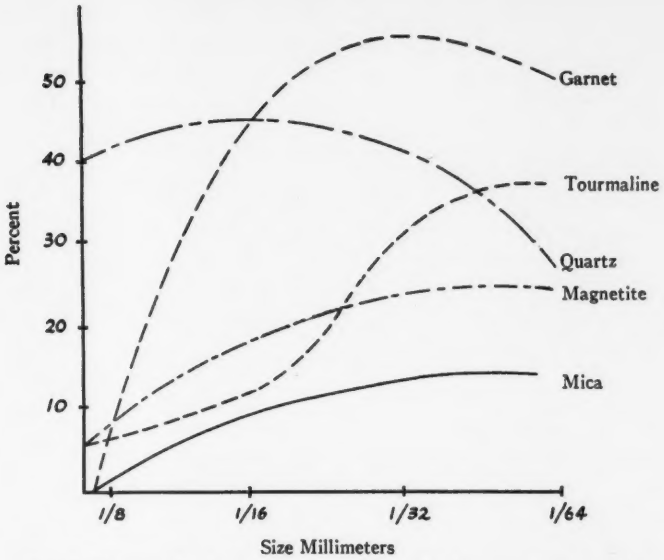

FIG. 2. Diagram showing variation of the minerals in respect to size grade.

brown color, is unaltered by weathering and some of the flakes occur with the heavy minerals.

Magnetite. Magnetite is the most abundant of the heavy minerals and is found chiefly in the sandstones. The grains are silver-gray in color, exhibit black metallic luster in reflected light and are free from oxidation. The crystal form can be determined in about 50 per cent of the cases. The others are irregular with rounded edges.

Tourmaline. Tourmaline is second to magnetite in abundance but is more evenly distributed throughout the formation. Brown, pink and colorless varieties are present with the last in the minority. Most of the grains show the crystal form with rounded ends. Some particles of the brown variety are well rounded and contain needle inclusions.

Pyrite. Cube and pyritohedron crystals occur as disseminated grains well distributed throughout the formation. The mineral is of the characteristic brass-yellow color with well developed striae on the cubes.

Garnet. Garnets occur as dodecahedron crystals of the alamandine variety. The mineral is brownish-red in color. Many of the crystals are coated with iron oxide. The grains have not undergone extensive transportation as the crystals are well developed and without etched or pitted surfaces.

Iron oxide. The iron oxide particles are irregular in shape and consist of limonite and hematite. The particles are abundant and well distributed

throughout the formation. Many shells of micro-organisms have been replaced with the iron oxide.

Distance From Base	Magnetite	Tourmaline	Biotite	Pyrite	Garnet	Iron Oxide	Quartz	Muscovite	Gypsum	Glauconite
97	•		•			•	•	•		•
94	•	•	•	•		•	•	•		•
90	•						•			•
88	•					•	•		•	
82				•	•		•			
80	•					•	•			•
74	•	•	•			•	•	•	•	
70	•	•		•			•		•	•
66	•	•				•	•	•		
60	•	•	•				•			•
56	•	•					•			•
52	•	•	•	•		•	•	•		
45	•	•	•				•			•
36	•	•	•				•	•		
28	•	•	•	•		•	•		•	
25	•	•	•			•	•	•		
16	•	•	•			•	•	•		
10	•	•		•	•	•	•			•
5	•					•	•	•		•
1	•	•			•		•	•		•

FIG. 3. Distribution of the minerals in the formation.

ENVIRONMENTS OF DEPOSITION

The sediments of Kiamichi were deposited in a shallow sea that extended from the Gulf northward into southern Colorado and Kansas (1). This environment is exhibited in the character of the sandstones, in the presence of gypsum, and in the abundance of fossils. The sandstones are cross-laminated, and are variable in thickness and texture within the same area. Gypsum is present in thin layers which are parallel to the bedding planes. Mullusks (*Gryphaea*) are abundant and suggest marginal conditions.

ORIGIN OF THE MINERALS

The area adjoining the Kiamichi sea was low and made up of non-marine Triassic sediments (1). Such conditions would be favorable for decomposition to exceed disintregration. The above is indicated by; 1. the minerals are angular and often the crystal form can be determined. Apparently they have not been transported a great distance or undergone extensive wear. 2. such minerals as feldspar are absent as there was sufficient time for them to be removed by climatic conditions. 3. practically all the minerals will pass through a 96-mesh screen which suggests a low region of average relief.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 1, PP. 35–47, FIGS. 1–5, TABLES I–II, APRIL, 1936

APPLICATION OF LOGARITHMIC MOMENTS TO SIZE FREQUENCY DISTRIBUTIONS OF SEDIMENTS

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ABSTRACT

A symbol for the negative logarithm of grain diameters to the base 2 is introduced as a device for statistical computation. The advantages of the symbol are that it simplifies geometric grade scales, it permits the application of common statistical procedures to the data, and yet it yields directly a series of values which express the logarithmic properties of the size frequency curve. By means of a simple chart the logarithmic values may be converted to their "diameter equivalents" it desired. An example is included of the application of the symbol to a statistical technique based on the moments of the distributions, and the significance of the measures thus obtained is discussed.

In relatively recent years emphasis in sedimentary petrology has shifted from isolated rock samples to suites of samples, collected with a view of obtaining more complete knowledge of the formation being studied. This change has brought with it a growing realization of the need for statistical analysis of the resulting data, as numerous papers on the subject demonstrate. Unfortunately, the use of common statistical measures has been somewhat limited by the unequal intervals of the grade scales used in presenting the data. Thus workers in sedimentary petrology have had to develop their own statistical techniques. The net effects of this situation have been two, in the main. First, measures have been adopted that lend themselves directly to data arranged in unequal classes, such as the median and the quartiles, and second, graphic methods have largely been used because of their relatively greater convenience.

Sedimentary petrologists at present use a wide range of statistical devices, including numerous empirical methods of characterizing the sediments, but among common methods is one conspicuous by its absence. This is the method of moments.[1] Wentworth (1)* developed a technique based on moments, but because of the complexity of his computations, and the unsatisfactory manner in which his theory was presented, little use has been made of it. Hatch and Choate, (2) at about

[1] The moments of a frequency distribution are parameters or constants that describe the properties of the distribution. In ordinary statistical practice the first moment is the *arithmetic mean*, and the second moment is the basis of the *standard deviation*. The moments as used in this paper will be discussed more fully below.

* Numbers in parentheses refer to bibliography and comments at the end of this paper.

the same time, defined a series of logarithmic measures and developed graphic methods for frequency data that plotted as straight lines on logarithmic probability paper. Other techniques have been developed, but have not been widely used by geologists.

The thesis of the present writer is that as long as the uses of statistical measures are mainly descriptive and comparative, as they are in sedimentary petrology at present, the widest possible choice of methods should be available, so that any situation that arises may be attacked in the manner best suited to the data themselves, or to the problem at hand. In this connection a method of moments, as applied to the frequency curves of sediments, offers an important and significant method of attack. The moments of the distributions have been more extensively studied, and they have been related more closely to the probabilities underlying the distributions, than have any other statistical measures. Thus there is available a large body of statistical technique which may be drawn upon if a satisfactory method of moments may be applied to sediments. The chief difficulty in the past has been due largely to the unequal intervals, but this difficulty is not insurmountable.

From an understanding of the underlying problem presented by the unequal intervals, and by a proper choice of logarithm, not only may the curves be greatly simplified during plotting, but the data themselves may be treated by arithmetic methods no more tedious than the usual procedure of computing the moments in common statistical practice. Moreover, the use of logarithms in this manner results in the computation of *logarithmic moments*, which it will be shown are directly applicable to sedimentary data. Thus the statistical devices used by sedimentary petrologists at present can be supplemented by an entirely different method of approach, which opens other possibilities in the direct use of conventional statistical procedures with the data.

It is the purpose of the present paper to describe a method of moments as applied to sedimentary data, and to stress the significance of the resulting measures in evaluating the size frequency distributions of sediments.

THE SYMBOL ϕ

The discussion in the following text will proceed from first principles, so that the steps involved in the method may be developed in logical sequence. In most mechanical analyses the data are assembled in classes according to the Wentworth grade scale (3) in which each succeeding grade is half as large as its predecessor. Thus the class 1/2–1/4 mm. is followed on the right by the class 1/4–1/8 mm., an interval half its size. If the grade scale is plotted on ordinary arithmetic graph paper, the grades rapidly decrease in width as the scale is followed to the right, due to the convention of plotting the coarser grades at the left. Similarly a histogram or frequency curve

plotted on such a scale will be quite unsymmetrical, with much of the material assembled at one end or the other. (See Fig. 1.) In this direct plotting of the diameter along the horizontal axis, and frequency along the vertical axis, the diameter is chosen as the *independent variable;* i.e., the particular frequencies found depend upon the presence of diameters of such a size, rather than the reverse.

It has long been common practice to plot the classes equal in width both to simplify the diagram and to give equal significance to each grade. The increased symmetry of the resulting frequency curve is ample justification for the procedure. Actually, of course, the logarithms of the diameters are being plotted when the classes are drawn equal in width, which means that for the independent variable *diameter* is being substituted the independent variable *log diameter*. This change of independent variables thus serves an immediate and easily recognized purpose. (See Fig. 2.)

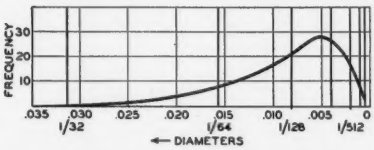

FIG. 1. Frequency curve of a Pennsylvanian underclay, showing frequency (*dependent variable*) plotted against diameters in mm. (*independent variable*). The heavy ordinates represent the Wentworth class limits. Note the lack of symmetry of the curve.

That the intervals become equal when logs are used is easily shown. Thus $\log_{10}2 = +0.301$; $\log_{10}1 = 0$; $\log_{10}(1/2) = -0.301$. Here each class is equal in width (interval = 0.301), with the origin at 1 mm. Note that the logs of numbers smaller than 1 are negative, and further, that if the base 10 is used, the class limits are not marked by integers. This suggests that logs be taken to such a base that each class limit is an integer, and this is accomplished by using the base 2. Then $\log_2 2 = +1$; $\log_2 1 = 0$; $\log_2(1/2) = -1$, etc. Notice, however, that negative values still apply to diameters smaller than 1 mm. Now, there probably are more fine-grained sediments (sands, silts, clays) than there are gravels, so that most analyses will lie in the range below 1 mm. This suggests that negative logs be used, both to avoid negative numbers in this important range, and also to convert the grade scale to one which increases to the right, as most ordinary scales do. By using negative logs, then, the scale is simply reversed, and the computations are in no wise made more difficult; indeed, they are often much simplified as the sequel will show.

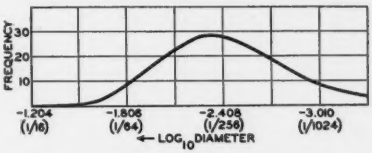

FIG. 2. Frequency curve of the same sediment as fig. 1, with *frequency* plotted against *$\log_{10}$diameter*. The Wentworth class limits are now equally spaced, and the curve is much more symmetrical.

For computational reasons it is advisable to adopt some name for

these negative logs of the grade scale, and the writer suggested in another connection (4) that the symbol ϕ be used for this purpose. The substitution involved is:

$$\phi = -\log_2 \xi \qquad (1)$$

where ξ is the numerical value of the grain diameter (or class limit) in mm., and ϕ is defined by the writer as the *Wentworth exponent*, from the exponential form of equation (1), $\xi = (1/2)^{\phi}$, and from its application to the Wentworth grade scale. With values of ξ equal to 2, 1, 1/2, ξ equals -1, 0, $+1$, respectively. Thus ϕ increases with decreasing grain diameters, and the Wentworth scale becomes arithmetic, with $\phi = 0$, ($\xi = 1$ mm.), as the origin. It is possible to interpolate arithmetically on this scale, and to express all grain diameters in ϕ-terms directly. The conversion of one symbol to the other, by means of a simple chart, will be discussed below. For purposes of reference, Table 1 shows the ϕ-values of the Wentworth grade limits from 32 mm. to 1/1024 mm. One immediately apparent advantage accruing from the ϕ-scale is the elimination of unwieldy fractions or decimals, such as 1/1024 mm. (0.00098 mm.). These inconvenient values become simply $+10$ on the new scale. The use of the symbol adapts itself equally well to the grade scale based on $\sqrt{2}$. The successive points along that scale are half-units on the ϕ-scale.

TABLE I. *Conversion of Wentworth grade limits from ξ to ϕ*

Grade limit in mm. (ξ)	ϕ	Grade limit in mm. (ξ)	ϕ
32	−5	1/8	+ 3
16	−4	1/16	+ 4
8	−3	1/32	+ 5
4	−2	1 64	+ 6
2	−1	1/128	+ 7
1	0	1/256	+ 8
1/2	+1	1/512	+ 9
1/4	+2	1/1024	+10

The substitution of ϕ for ξ, then, merely involves a change in the independent variable, such that the intervals between class limits become equal; each class is one unit in width; and the scale of values increases to the right. Hence it is possible to use the mechanical analysis data arranged according to the ϕ-scale for the computation of a whole series of statistical measures, many of which may be adopted directly from standard statistics texts, with no changes in procedure (5). The resulting measures, furthermore, may be used directly to characterize the frequency curve, they may be used in connection with Gram-Charlier series, they may be used in estimating areas under the curve—in short, many aspects of conventional statistical analysis become available. On the other hand, the measures may be converted to their "diameter equivalents" if desired.

It should be emphasized at this point that the use of any statistical measure does not depend upon the fact that the independent variable has an immediately comprehensible significance; it depends only on the fact that a curve is given. This is equally true of frequency curves plotted on the basis of ξ, $\log_{10}\xi$, or ϕ. Furthermore, it is not necessary that there be simple relations between the measures in terms of one independent variable, with those based on some other independent

variable. True, it is often desirable to have such simple relations, and in the present case the mean value of the ϕ distribution bears quite a simple relation to a mean value of the ξ distribution. Similarly the second moments are not unduly complex in their relations, but this is probably not true for higher moments. These relations will be discussed below; the remarks are included here both to establish the approach and to avoid possible misunderstandings.

APPLICATION OF ϕ TO THE METHOD OF MOMENTS

An interesting feature of the ϕ-notation, which renders it a favorable choice for the computation of the moments of the frequency distributions of sediments, is that in any frequency distribution the arithmetic mean of the ϕ-values is a logarithm of the geometric mean of the ξ-values,[2] Thus it is only necessary to find the arithmetic mean of the ϕ-distribution to obtain a log geometric mean that serves well as a central point about which the moments of the curve may be computed. Furthermore, the higher moments of the distribution, in terms of ϕ, may be found by following standardized statistical procedures, thus obviating the necessity of devoloping new techniques of computation. In this manner a series of measures corresponding to the *mean size*, the *standard deviation*, *skewness*, and *kurtosis* may be obtained, with, however, this important distinction: *the values obtained by the computations with ϕ will be logarithmic measures in terms of the log geometric mean instead of arithmetic measures in terms of the arithmetic mean.* Once these measures have been found they may be used directly in describing the characteristics of the curve. To develop these points, it may be well to furnish an actual example of the computations.

In computing the statistical values of a sediment in ϕ-terms, one may follow directly the standardized procedures given in statistics texts for finding the arithmetic mean, the standard deviation, (and skewness and kurtosis, if these last values are desired) (6). The use of the ϕ-notation in these standard procedures yields logarithmic moments directly, as has been pointed out. The following example follows the standard practice directly, except that a few notational changes have been made, so that the interested reader may trace the relations of the moments to one another. A tabular series of values is set up, as shown in Table 2. For simplicity the data (7) are arranged in Wentworth classes, although classes based on $\sqrt{2}$ could just as well be used (8). Column (1) shows the grade limits in diameters (ξ), column (2) the same limits in ϕ-terms, and column (3) lists the weight percentage frequencies (f) in each grade. In column (4) the maximum grade has been chosen as the arbitrary zero-point of a deviation or d-scale, and the grades above and below are numbered in sequence as negative and positive, respectively. In column (5) the f of each grade in column (3) has been multiplied by the corresponding d from column (4), to yield a series of values called fd. These are

[2] This relation is proved in the Appendix to this paper, which also discusses several other theoretical points.

added algebraically, and the final sum written below. In this case it is +31.5. Next the d's are squared and entered in column (6). These are then multiplied by the frequencies from column (3), to yield the fd^2 values of column (7). Again a total is struck, here 41.7. Column (8) contains the cubes of the d's, and the fd^3 values of column (9) are found by multiplying the values of column (3) by those of column (8). The algebraic total, +32.7, is written below.

TABLE II. *Computation of the moments of the size distribution of beach sand from southern shore of Lake Michigan*

(1) Grade limits in mm. (ξ)	(2) Grade limits in ϕ	(3) Per cent by weight (f)	(4) d	(5) fd	(6) d^2	(7) fd^2	(8) d^3	(9) fd^3
1–1/2	0–1	4.9	−1	−4.9	1	+4.9	−1	−4.9
1/2–1/4	1–2	58.9	0	0	0	0	0	0
1/4–1/8	2–3	36.0	+1	+36.0	1	36.0	+1	+36.0
1/8–1/16	3–4	0.2	+2	+ 0.4	4	0.8	+8	+ 1.6
Totals		100.0		+31.5		41.7		+32.7

These several values are now each divided by the total frequency (100), and the results written to one side, as follows. The value 31.5/100 = 0.315 is called n_1, the first moment about the origin of the d-scale. From column (7) is obtained 41.7/100 = 0.417, called n_2, the second moment about the d-origin. Finally, from column (9), 32.7/100 = 0.327, called n_3, the third moment about the d-origin. From here on standard formulas are used in determining the statistical values; the theoretical derivation of these formulas may be found in statistics texts (Camp) (6).

The *arithmetic mean* of the ϕ-distribution, called M_ϕ, is found by adding n_1 to the mid-point of the d-scale, here 1.5 (in ϕ-units). This yields $M_\phi = 1.500 + 0.315 = 1.815$.

The *standard deviation* of the ϕ-distribution, σ_ϕ, is $\sigma_\phi = \sqrt{n_2 - (n_1)^2}$. Now $n_1 = .315$, and hence $(n_1)^2 = 0.099$, so that $\sigma_\phi = \sqrt{.417 - .099} = \sqrt{.318} = 0.563$.

The *skewness* is more complicated. The third moment about the d-origin, n_3, must first be converted to m_3, the third moment about the mean, by using the standard equation $m_3 = n_3 - 3n_2n_1 + 2(n_1)^3$. This yields $m_3 = .327 - 3(.417)(.315) + 2(.315)^3 = .327 - .393 + .062 = -0.004$. From this point on one has a choice of several formulas for the skewness. We shall use the one based on $\alpha_3 = m_3/\sigma^3$. Skewness is then $Sk_\phi = \alpha_3/2$. In this example σ_ϕ is .563, so that $2\sigma_\phi{}^3 = .356$, and $Sk_\phi = -.004/.356 = -0.011$ (Camp) (6).

The *kurtosis* of the curve will not be computed here. It is based on the fourth moment about the mean, and involves a somewhat tedious computation. Interested readers will find

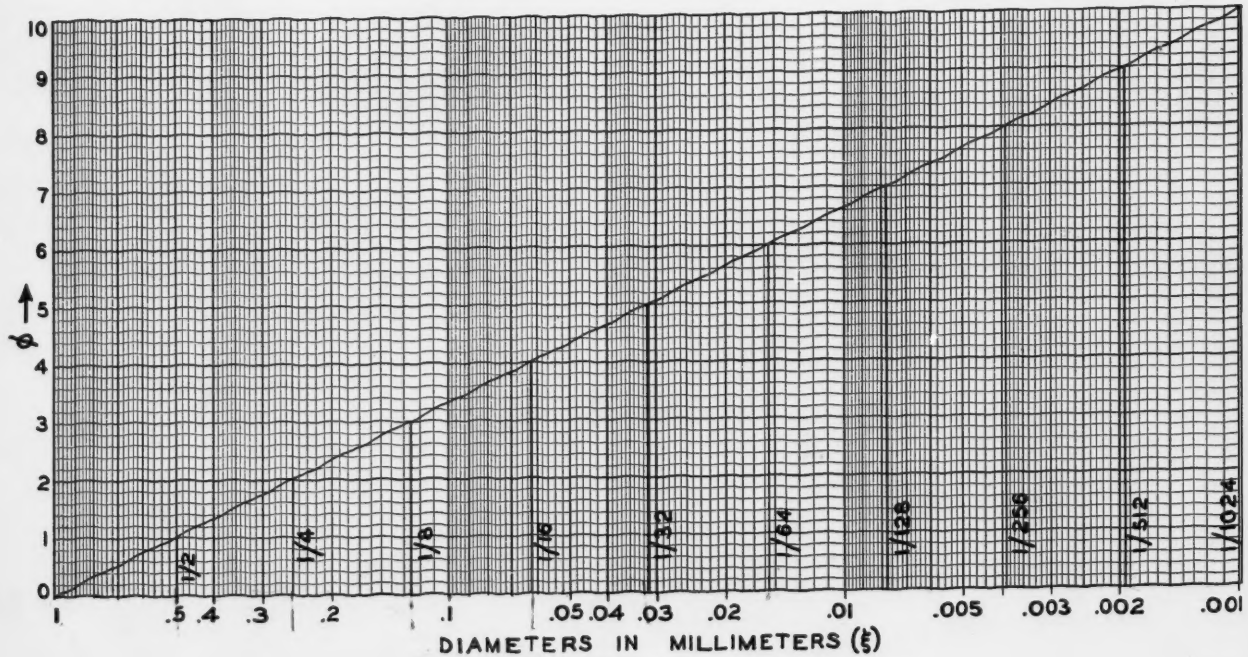

FIG. 3. Conversion chart for ϕ and ξ.

the necessary equations in Camp's book (see reference 6).

As a result of the computations described, three statistical values have been obtained for the beach sand:

$$M_\phi = 1.81$$
$$\sigma_\phi = 0.56$$
$$Sk_\phi = -0.01$$

These values may be used directly in describing and comparing the frequency curves, without converting them back to their ξ-equivalents. However, for purposes of comparing the ξ-equivalents with the above ϕ-values, a simple method of converting one symbol to the other may be described.

GRAPHIC CONVERSION OF ϕ TO ξ

For the conversion of fractional or decimal values of ϕ or ξ to one another, a simple conversion chart may be made with semi-logarithmic paper. By using Dietzgen 3-cycle paper #340–L310, a range of ten units along each axis may be had. Starting with the diameter $\xi = 1$ mm., at the left, the successive Wentworth scale points are laid off along the horizontal logarithmic scale. The values decrease to the right until 1/1024 (0.00098) is reached just a shade beyond the 0.001 point. The scale points will be about 2.4 cm. apart. Along the vertical arithmetic scale the point $\phi = 0$ is set equal to $\xi = 1$ mm., and each major division of the scale (about 1.2 cm. on the paper) is called a ϕ-unit. At the corresponding ξ-points ordinates are erected to the ϕ-values given in Table 1, and a diagonal line is drawn across the tops of the ordinates from (1, 0) to (0.00098, 10). The line makes an angle of about 28° with the horizontal. Figure 3 illustrates such a chart somewhat reduced, so that as shown it is too small for accurate work, but does yield approximate values.

The conversion of one symbol to the other thus becomes simply the reading of a straight line graph, and the charts may be made to represent any range of sizes desired. If it is preferred, however, the symbols may be transformed to one another by logarithmic computations.[3]

By referring back to the three values given above, we may illustrate the conversion of ϕ to ξ by Figure 3. The value of M_ϕ is 1.81; this point is located on the vertical axis, and by moving to the right until the diagonal line is met, the corresponding ξ- value is found to be 0.286 mm. Similarly the other two values are found, yielding the following numbers, where GM_ξ is the geometric mean of the diameters, σ_ξ is the "diameter equivalent" of σ_ϕ, and Sk_ξ is the "diameter equivalent" of Sk_ϕ. Specifically, the relations are $M_\phi = -\log_2 GM_\xi$, $\sigma_\phi = -\log_2 \sigma_\xi$, and $Sk_\phi = -\log_2 Sk_\xi$:

$$GM_\xi = 0.286 \text{ mm.}$$
$$\sigma_\xi = 0.676$$
$$Sk_\xi = 1.05$$

[3] To convert ϕ to ξ logarithmically, recall that $\log_{10}\xi = \log_{10}2 \log_2\xi$, and that $\log_{10}2 = 0.301$. Hence $\log_{10}\xi = 0.301 \log_2\xi$. But $\phi = -\log_2\xi$, so that $-0.301\phi = \log_{10}\xi$. When the resulting value is negative, it should be added to 10.000−10 to obtain a positive mantissa, before locating the antilog in common log tables.

SIGNIFICANCE OF THE LOGARITHMIC MEASURES

It will be advantageous to examine the two sets of statistical values obtained from the given example, in terms of the frequency curve of the sediment. For this discussion the mean value and the standard deviation will be treated in detail; the skewness will be mentioned later. Figure 4 is the frequency curve of the beach sand of Table 2, obtained by graphic differentiation of the corresponding cumulative curve (7). The horizontal scale shows ϕ as the independent variable, and the area under the curve represents the total frequency. At the point $\phi = 1.81$ an ordinate has been erected. This is

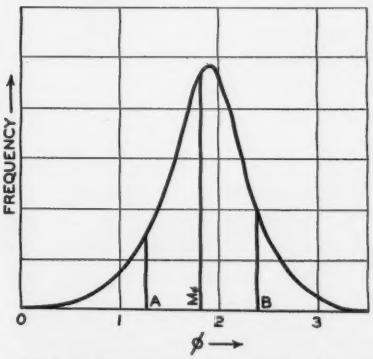

FIG. 4. Frequency curve of beach sand (Table 2) with ϕ as the independent variable. Each unit on the horizontal scale is one Wentworth grade. The distance between ordinates A and B measures the spread of the curve.

M_ϕ, the arithmetic mean of the ϕ-distribution, and it passes through the center of gravity of the distribution. Hence it serves as a measure of the average value of the distribution.

The relation of the standard deviation, σ_ϕ, to this mean may readily be seen from Figure 4. Since σ_ϕ is expressed in ϕ-units, it measures the distance directly in class intervals from the mean to the center of gyration of each half of the curve. Hence

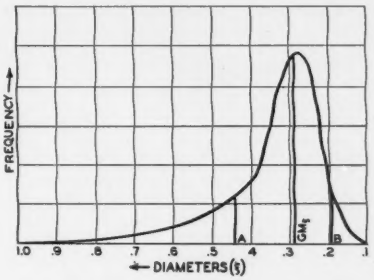

FIG. 5. Frequency curve of the same sediment as fig. 4, with diameters in mm. (ξ) as the independent variable.

it tells directly how many Wentworth grades are included in the central part of the curve on either side of the mean. The value $\sigma_\phi = 0.56$ means that in the distance $M_\phi - \sigma_\phi$ to $M_\phi + \sigma_\phi$ there are 1.12 Wentworth grades, entirely independently of whether the sediment is coarse or fine. Thus σ_ϕ is a measure of the degree of scatter about the mean value. Consequently it serves as a measure of the "sorting" of the sediment, at least in a descriptive sense.

To locate the ordinates marked A and B in Figure 4 it is only necessary to move 0.56 ϕ-units (grade sizes) to the left and right of the mean value. Point A is $M_\phi - \sigma_\phi = 1.81 - 0.56 = 1.25$, and B is $M_\phi + \sigma_\phi = 1.81 + 0.56 = 2.37$. Between these two ordinates,

then, is the central portion of the distribution.[4]

We may now turn to the "diameter equivalents" of the measures just discussed. To evaluate these in terms of the frequency curve, the curve itself may be drawn with the diameters (ξ) as independent variable, as in Figure 5. At the point $\xi = .286$ an ordinate is erected. This is the geometric mean of the distribution. To locate ordinate A, divide GM_ξ by σ_ξ: $.286/.676 = 0.421$; to locate B, multiply GM_ξ by σ_ξ: $.286 \times .676 = 0.193$.[5] These two ordinates are shown in the figure. Notice that just as the frequency curve itself is drawn out to the left when ξ is used as the independent variable, so the spread between A and B is drawn to the left with respect to the geometric mean. In fact, GM_ξ is itself the geometric mean of the ξ-values at A and B.[6]

A comparison of Figures 4 and 5 suggests that σ_ϕ is a more readily visualized measure of the characteristics of the sediment than σ_ξ, although in particular cases the latter may have distinct advantages. It is a point that requires further attention.

The skewness of the curves has not been included in the above discussion for several reasons. One of these is that unless one is certain he has a single homogeneous population in the sample, the single curve may represent a mixture of two distributions (9). This is of decided significance in the study of sediments because it is often not possible to determine whether the sample is homogeneous, or whether during its collection two or more distributions may not have been included. Further, diagenic changes may conceivably affect the normality of the curve, and such factors cannot at present be evaluated. Nevertheless, the skewness may afford important data. Sudden changes in its value in a series of related sediments may indicate sampling difficulties or even genetic changes. In this respect the kurtosis of the curves may also be significant.

In a geometrical sense the skewness of the curve may be interpreted as a measure of the relative spread of the data on one side or the other of the mean. Thus it is a measure of the departure of the curve from normality or symmetry, and the sign before the value indicates the direction in which this departure occurs. In the curve of Figure 4 the skewness is negative, and hence toward the negative ϕ-scale. An easy way to visualize skewness is to recall that in a normal curve the mean, median, and mode all coincide, whereas with increasing skewness these values spread apart. The extent of their spread, except in extreme cases, may be used as a measure of the skewness (6, p. 166).

Entirely aside from skewness as a descriptive and comparative measure for sediments, the third moment (on which the skewness is based) is im-

[4] In a perfectly normal distribution, symmetrical about the mean, the interval between the ordinates A and B would include about 68 per cent of the distribution.

[5] These manipulations follow from the fact that when M_ϕ and σ_ϕ are added, GM_ξ and σ_ξ must be multiplied, and when σ_ϕ is subtracted from M_ϕ, GM_ξ is divided by σ_ξ.

[6] Thus, $GM_\xi = \sqrt{(GM_\xi/\sigma_\xi)(GM_\xi\sigma_\xi)}$.

portant in fitting an equation to the curve and in smoothing the data. When the third moment is so small that it may be neglected, the data may be assumed to approximate normality, with the result that curve-fitting is tremendously simplified. The third moment of the curve in Figure 4 is -0.004, which is practically negligible, while the third moment of Figure 5, computed about the *arithmetic mean* of the ξ-values, is found to be approximately 0.24, a value not negligible, as the curve itself indicates. Now in all statistical computations, they are simple in proportion as the higher moments may be neglected. Thus the use of ϕ as the independent variable has greatly simplified the statistical approach in this instance, and it is the resulting simplification that "justifies" the substitution of ϕ for ξ in sedimentary analysis.

SUMMARY

The principal points stressed in this paper have been that the disadvantages arising from the use of unequal class intervals in sedimentary analysis may be offset by the substitution of a new independent variable for the usual diameter values. The use of ϕ as the new independent variable serves this purpose, and makes available a series of statistical measures based on the moments of the distributions. In the present instance the definitions of the parameters involve weight percentage frequencies, inasmuch as the method is applied to conventional mechanical analysis data. The question of other frequencies, such as number frequencies, introduces additional factors into the discussion. Obviously a new series of ϕ-measures may equally readily be defined in terms of number frequency, volume frequency, and so on. Measures on such different bases need not necessarily bear simple relations to each other.

The whole subject of statistical analysis as applied to sediments is still largely an open field, and there are practical difficulties in predicting which set of measures best adapt themselves to a genetic study of sediments. The obvious implication is that workers should express their results in more than one manner, so that the data be available as and when needed. At the present stage of development it seems desirable to use several techniques rather than any single approach which may by its limitations mask significant points points about the sediment. The method of moments, in this connection, affords a means of supplementing the quartile measures commonly used by sedimentary petrologists.

The writer takes pleasure in acknowledging his indebtedness to Dr. Carl Eckart of the Department of Physics of the University of Chicago for his friendly criticism and many helpful suggestions during the preparation of this paper.

APPENDIX

The choice of the arithmetic mean of the ϕ-distribution, M_ϕ, and the standard deviation in ϕ-terms, σ_ϕ, as the parameters of the size frequency distribution, permits an ex-

pression of the normal distribution in the ϕ-notation as

$$y = \frac{1}{\sigma_\phi \sqrt{2\pi}} e^{-(\phi - M_\phi)^2 / 2\sigma_\phi^2}$$

where ϕ is the value of the independent variable at any point. The analogy to the normal probability law is apparent. The relations between the normal law in ϕ-terms and in ξ-terms have not been fully examined by the writer, but they are doubtlessly complex. However, there is no necessity for simple relations, inasmuch as it is not necessary to convert the ϕ-distribution to its ξ-equivalent in order to describe the distribution.

It happens that the choice of independent variable in the present case affords a fairly simple relation between the arithmetic mean of the ϕ-distribution and the geometric mean of the ξ-distribution. Thus, by definition, $M_\phi = \frac{\phi_1 + \phi_2 + \cdots + \phi_n}{n}$, where ϕ_1, ϕ_2 are individual values of the variable. However, $\phi = -\log_2 \xi$, so that $M_\phi = -\log_2 M_\xi = \frac{\log_2 \xi_1 + \cdots + \log_2 \xi_n}{n}$ where M_ξ is some mean of the ξ's. The antilog of this expression is $M_\xi = \sqrt[n]{\xi_1 \xi_2 \cdots \xi_n}$, so that M_ξ proves to be identical with the usual definition of the geometric mean of the diameters, called GM_ξ in the text. Higher moments of the ϕ-distribution increase in complexity when expressed in ξ-terms; the geometrical relations between the second moments was pointed out in the text in conjunction with Figures 4 and 5.

One of the advantages of a choice of independent variable such as the present is that when the sedimentary data plot as a symmetrical curve in ϕ terms, the third and higher moments may be neglected, and the data may be used in conjunction with tables of the probability function, both for determining areas under the curve and for smoothing the data; in addition it yields a simple equation for the curve, the parameters of which (M_ϕ and σ_ϕ) uniquely determine the frequency distribution. However, even when the curve is not symmetrical, the higher moments of the ϕ-distribution may be used to build up a form of the Gram-Charlier series, of which the normal ϕ-curve is the first term. Thus in any except extreme cases of asymmetry, detailed statistical analysis is possible by conventional procedures. Further, such measures as the Chi-square test may be used to determine the goodness of fit of such smoothed curves. The writer has in preparation a paper on these aspects of the method, which will appear in an early issue of this *Journal*.

It is interesting, in connection with the ϕ-notation, that the method of moments developed by Wentworth (see footnote 2, text) yields values practically identical with those of the ϕ-method. As far as the writer can trace the steps in Wentworth's procedure, he actually computes moments with respect to a log of the geometric mean, although in his discussion he appears to confuse this with the arithmetic mean.

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5. Since ϕ is a logarithm, operations involving multiplication, division, or the extraction of roots in ξ-terms reduce merely to addition, subtraction, and simple division in ϕ-terms. Thus, such measures as Trask's sorting coefficient and skewness (Trask, P. D., *Origin and environment of source sediments of petroleum*, 1932, pp. 68–76) may be very simply computed, since not even a slide rule is needed.
6. MILLS, F. C., *Statistical Methods*, New York, 1924, describes the method of finding the arithmetic mean on p. 118, and the standard deviation on p. 156, in the first 6 columns of the table. Skewness and kurtosis are not included, although the former will be included in

the example below. For the necessary conversion equations needed in computing skewness and kurtosis, see Camp, B. H., *The mathematical part of elementary statistics*, New York, 1931, chapter 2.

7. The data used are the mechanical analysis of a beach sand. See Krumbein, W. C., The probable error of sampling sediments for mechanical analysis, *Am. Jour. Sci.*, vol. 27, 1934, p. 208, sample 7a.
8. When the data are arranged in Wentworth grades, the statistical values are expressed directly in the Wentworth grades as units. When the $\sqrt{2}$ or $\sqrt[4]{2}$ scales are used, constants depending on the new class sizes must be used to obtain comparable values. See Mills, (6) in this connection. Other things being equal, of course, the use of smaller classes will yield closer approximations to the true values of the statistical measures.
9. PEARSON (*Phil. Trans. Royal Soc.*, vol. 185A, 1894), has shown that a skew curve may be broken down into two normal curves, even if the original curve is unimodal. For a possible genetic significance of skewness, see Gripenberg, Stina, A study of the sediments of the North Baltic and adjoining seas, *Fennia*, vol. 60, no. 3, 1934, p. 203.

REVIEWS

Beach Erosion Board, Office of the Chief of Engineers, U. S. Army, *Interim Report.* Washington, Apr. 15, 1933. 99 pp., 19 figs. $0.25.

This report of studies carried on by the U. S. Army Engineers, which contains a great deal of information of value to students of shore sediments and processes, seems to have escaped the attention of many workers. From the geologist's point of view, the most important object of the investigations was "to undertake a general scientific investigation to determine the natural forces causing coastal changes, and the best methods to control them. This included experiments to discover and *measure* the natural forces involved, and to test previous and new hypotheses as to such forces—."

The studies which bear on geological problems are as follows; (a) Studies of sand characteristics and sand movement along the shore, included in the following experiments;

Visual determination of sand movement offshore by a diver.

The effect of currents, winds from various directions, and storms on the profile of the foreshore.

The sand content of water, at varying distances from the plunge point and from the bottom.

Visual determination of sand movement near the waterline by colored sand.

The size and character of materials composing the beach sands and the relation between their diameters and the slope of the foreshore.

Investigation of the direction of sand movement offshore to determine whether or not there was a tendency to move sand towards shore.

Investigation of the theory of sand waves.

(b) Studies of currents existing along shore and their causes, included in the following experiments;

Investigation of the strength and direction of ocean currents near shore caused by tides and winds, and determination of the residual currents.

Determination of the orbital velocity of water particles due to wave action.

(c) Studies of characteristics of wave action and force of wave action, included in the following experiments;

Determination of wave velocities, wave heights, depths of water in which waves break, and wave profiles.

Determination of the energy of waves from their profiles.

Determination of the striking force of waves, by dynamometers.

Characteristics of wave attack on the foreshore, including the undertow, the direction of the prevailing currents and the strength of the currents.

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EVANS, P., HAYMAN, R. J., and MAJEED, M. A., *The graphical representation of heavy mineral analyses,* Preprint No. 29, World Petrol. Congress, London, 1933. 6 pp.

The authors of this paper, and their associates in the Burmah Oil Company, India, have examined thousands of heavy mineral concentrates from the Tertiary rocks of Burma, Assam, and other regions, and they find that, in the absence of fossils, extremely valuable information can be gleaned from the mineral suites.

A good discussion of the methods of securing mineral frequencies is found in this paper. It is granted that under many conditions estimation may be necessary, but in the team work employed in large-scale operations, counting is indispensible. In no other way can the work of a number of individuals be collated. The mineral percentages so obtained are not, however, expressed in that form. The object is to attain some sort of graphical representation that will enable quick and accurate survey of a large number of analyses. The more usual methods of so doing are discussed —the fullest treatment the reviewer has seen —and the weaknesses of the histogram, "strip," and other methods are pointed out. These weaknesses are usually that the varia-

tion of a single sample is masked in the averaging necessary to make a histogram.

The method finally adopted and used with conspicuous success is that of using arbitrary numbers to stand for certain percentages:—0 equals "absent"; 1* equals 0–½%; 1 equals ½–1%; 2, 1–2%; 3, 2–3%; 4, 5%; 5, 10%; 6, 20%; 7, 40%; and 8 equals 80%. The range of any one number is made somewhat smaller by the use of minus and plus following the number. The advantage of this method is that it gives importance to the small percentages, that it is logarithmic except for the lower values, and that it permits, as a result of the latter fact, a compact representation that histograms never have. The plotting is carried out as follows:

Let it be supposed that there are a number of samples taken either at regular stratigraphic intervals, or, if the sequence be unknown, at some regular interval along the traverse. For each heavy mineral species in the samples a separate diagram, or "range table," is constructed. In its construction the samples are plotted, as some 5 to 20 evenly spaced points per inch, along the horizontal axis in their stratigraphic, or "natural" order. Then at each point is erected a perpendicular which, by its length, expresses the frequency of the mineral species for that particular sample. (A length of 1/10 inch was employed for each frequency number.) The tops of all the vertical lines so constructed are joined, giving an area enclosed by an irregular line at the top. This area may be colored to make it stand out from similar range tables for the other mineral species—the range tables being placed vertically below one another in such a way that all points for the same sample lie on a vertical line.

On the whole series of range tables one puts the names of mineral species corresponding to each, as well as any stratigraphic or lithologic information available. For example, one can separate known stratigraphic horizons by strong vertical lines running through all the diagrams.

To realize the ease with which one can read off changes in heavy mineral proportions one must see such range tables constructed. They are similar to variation diagrams used in the study of igneous rocks, although, because of their essentially logarithmic vertical scale, they show none of the tremendous "ups-and-downs" of those diagrams. To the reviewer's mind, they represent the most useful graphical method yet devised for showing the variations in heavy mineral content of a large number of samples.

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LEINZ, VIKTOR, *Ein Versuch, Geschiebemergel nach dem Schwermineraliengehalt stratigraphisch zu gliedern*, Z. f. Geschiebeforschung, vol. 9, pp. 156–168, 1933.

According to Leinz, very little work has been done on the heavy mineral composition of the various German tills. The author, therefore, sets himself the task of determining whether this type of investigation will be useful in differentiating younger from older tills.

Most interesting to one not conversant with the local geology are Leinz's methods of work. First, he recommends the collection of a 50–80 gram sample, which is then sieved, heavy minerals being separated from the 0.10–0.06 mm. grade. He finds that the coarser grades contain non-representative amounts of certain minerals. The smaller grades are harder to work with since they cannot be sieved, and the small mineral grains are much more difficult to identify. Separation is carried out with bromoform. In no case is estimation resorted to, some 600 grains being counted in each sample. The error between a count of 400 grains and one of 800 grains is said to amount to about 3% for the commoner species and as much as 20% for the rarer ones—figures which agree approximately with results obtained by the reviewer.

The author makes a good point of testing different horizons of the same till at one locality to see if the heavy mineral content varies enough at that one locality to render worthless figures obtained from outcrops over a wide area. To that end he examines at one outcrop 6 samples taken about 2 meters apart stratigraphically. The heavy mineral content of these showed a remarkable uniformity. Then a few samples taken at intervals of several kilometers were tested, with a like result.

Finally, areal correlation of the same till was found to be possible by heavy minerals over a distance of some 30 kilometers.

The most novel part of the paper under review is the method of representing graphically the heavy mineral analyses. The author employs a triangular diagram of the type used commonly by workers in igneous rocks. In what seems to be a somewhat arbitrary manner, the minerals garnet, disthene, staurolite, and epidote are placed at one apex of the triangle, because they are dominantly metamorphic minerals. At another corner are hornblende, augite, olivine, and diopside—the "essential minerals" of the source rocks, and in the third corner the "pegmatitic" and "accessory" minerals zircon, titanite, apatite, rutile, corundum, and tourmaline. The analysis of any one sample is represented, then, by a single point. This point is plotted in the usual manner for such diagrams—by taking the total percentages for all those minerals in one corner and scaling this percentage the proper distance toward that corner along a perpendicular from the opposite side. Similar measurements are made for the other two corners of the triangle.

The kind of representation employed conveys, in this case, the point that Leinz is trying to make, but its general usage can hardly be envisaged. For one thing, there will be no unanimity of opinion as to which minerals should be assigned to which corner of the triangles, even when the same mineral species are being dealt with. More important than that, however, is the fact that the percentage of any one mineral species is submerged in the total for its group, so that two samples, one of which had 50% staurolite and the other no staurolite at all could have their compositions represented by exactly the same point. In this case the variation of the percentages of the other minerals of the group could hide the variation in staurolite.

Though general acceptance of the method of representation appears improbable, it does offer any one author dealing with uniform mineral suites a chance to show differences in heavy mineral compositions. Leinz's diagrams, for example, show two sharply separated fields of points—one for samples from a young till, and one for those from an old one. For this particular problem the results can be seen at a glance.

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FICHTER, HANS JAKOB. *Geologie der Bauen-Brisen-Kette am Vierwaldstättersee und die zyklische Gliederung der Kreide und des Malm der helvetischen Decken*, Inaugural-Dissertation, Bern, 1934. (Separatabdruck aus: "Beiträge zur geologischen Karte der Schweiz," Neue Folge, 69. Lieferung.)

This publication, some 130 pages in length, presents the results of 360 days field work in a comparatively small area about 60 miles southeast of Basel. The data are clearly presented, with a number of excellent diagrams of the stratigraphic and structural relations. Structure sections show the sort of complexity we have come to associate with Switzerland.

Fichter makes at least two contributions that are of interest to students of sediments: (1) study, of grain sizes by examination of a large number (500) of thin sections, and application of the information so obtained to stratigraphic problems; and (2) a further study of cyclic sedimentation in the Cretaceous rocks (chiefly) of the area studied.

The reviewer does not remember any other paper in which a study of grain size alone has furnished so much information. The two diagnostic minerals are quartz and glauconite, and not only their absolute, but even their relative sizes have meaning (see below). Especially easy to visualize and understand are the numerous columnar sections with subdivisions and type of lithology shown diagrammatically. Close beside the section is a curve whose ordinate is stratigraphic position and abscissa grain size of quartz and/or glauconite. Gradual changes in grain size are found as one goes upward through most of the beds, and abrupt changes mark the important boundaries. In each case the "reliability" of the curve is given by a statement of the number of thin-sections used in its construction. One may wonder what additional information would be made available through the application of Krumbein's recent work on thin-section mechanical analysis to Fichter's slides.

Several workers had previously found repeated cycles of sedimentation in the area of Fichter's study. However, the author proposes new terms and redefines old ones in the light of his own work. He purposely avoids comparing cyclic sedimentation found here with that known elsewhere.

A Sedimentationszyklus (old name) in this region is a pair of beds or series of beds beginning with (1) a glauconitic fossiliferous layer, changing quickly into (2) a shaly or schistose bed with bathyal habit, which itself changes gradually and continuously upward into limey beds with neritic facies. Following these shallow water beds comes another bed like (1), and so on through the many cycles known.

The second bed (2) had been called by Klupfel an *Emersionszyklus* (hereafter indicated by "E"), and Fichter uses this name but redefines it to mean the following: a series of beds which change gradually upward in character from relatively bathyal to relatively neritic sediments. In this sense the term corresponds to the two terms *Inundationsphase* and *Regressionsphase* of Arbenz. The fossiliferous bed, or beds, (1) lying between two such *Emersionszyklen* ("E's") is called a Zyklengrenze (hereafter indicated by "Z") by Fichter.

The bathyal character of the lower part of an "E" is shown by the sediment itself—fine grained mud rock—and by the fauna, which is made up of nothing more than sponge spicules and radiolaria. Gradually the lithologic and faunal character changes and beds of limestone come to occupy more and more of the section, and in them are found more and more animals of shallow water habit. Banks of fossil oysters are found near the top of the series. A possible explanation for these facts is the filling up of the basin of deposition, but this cause is unacceptable in many cases in which the thickness of the series is inconsiderable (sometimes less than 25 meters). Therefore one must assume an as yet unexplained rising and falling sea-level,—though the position of the area at the edge of the Alpine geosyncline invites a host of tectonic explanations.

The *Zyklengrenzen* ("Z's") are thin (fraction of a meter to a few meters thick) fossiliferous beds often containing phosphatized fossils. Usually there is a sharp boundary against the adjacent "E's" both above and below, but there are sometimes transition beds at the base. The depth of water in which these beds accumulated is not definitely known, but it can be inferred from the following line of reasoning: the top of an "E" was formed in shallow water; following it is a "Z," and then comes the bottom of an "E" indicating deep water. Therefore, the "Z" probably represents sediment deposited during *deepening* of the sea. This conclusion is borne out in at least one case by the nature of the fauna, which changes from oysters at the base to an almost pure cephalopod fauna of bathyal aspect toward the top. A further interesting point is that a "Z" may interrupt at any time an "E," so that the latter might have been at any stage of shallowing when stopped by the deepening which gave rise to a "Z." In this sense the two different kinds of beds seem to arise from two antithetical movements.

A petrographic study of the sediments of the two series shows a consistent difference which can be used to separate them. The quartz grains of an "E" are always rather well graded, but in a "Z" there are many different sizes mixed together. Furthermore, in an "E" the size changes gradually from bottom to top of the series, becoming larger and larger in such a regular way that a thin-section will often prove from what part of the "E" the sample was taken.

Glauconite can be present in the "E's" just as well as in the "Z's," but in the former it is always about the same size as the quartz grains, in the latter almost always significantly larger than quartz. Though there are two kinds of glauconitic rocks present, a thin-section serves to distinguish them immediately. Further differences are the almost complete absence of other minerals (except calcite) from the "E's" and the presence of phosphorite, pyrite, and iron-rich carbonates in the "Z's."

The "E's" contain few fossils which can be used in dating exactly, but the "Z's" are often abundantly fossiliferous. In a way, the number and variety of fossils may be said to impose a hardship, for on examination there are found to be present, in the same thin bed,

ammonites known elsewhere to occur in different zones. Though this fact can be interpreted in many ways, the only satisfactory interpretation is that which regards the faunas of the "Z's" as "condensed faunas" (term not used by Fichter). The "Z's," then, represent periods of very slow sedimentation, and very slow sinking, during which time there were mixed together the fossils of all the ages spanned. The "E's" represent blanks in the paleontologic succession, and it is in just their position that many of the English ammonite zones are missing in the area studied.

Fichter has made some interesting contributions to the study of sediments, though they are but incidental to his work as a whole. He has stressed the detailed examination of very thin lithologic units, and has clearly shown the importance of checking field evidence by laboratory methods,—in his case by the determination and representation of absolute and relative grain sizes of different constituents as functions of stratigraphic position and lithologic variation.

He states (p. 96) that two other workers have found it impossible to differentiate the various *Sedimentationszyklen* by means of "purely petrographic investigations." If this phrase includes study of heavy mineral content, it forestalls a suggestion of the reviewer that, in view of the great length of time shown by the character of both the "E's" and the "Z's," one might expect the successive *Sedimentationszyklen* to show some differences in mineral composition.

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